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Testing of Machinability by Radioactive Methods

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ERRATA

Page 20, line 3 for V_B, φ, and read V_B, τ, and
» 26, » 19 for $\mu_e = 1{,}5$ mg read $\mu_C = 1{,}5$ mg
» 35, table VI, column head for $V_B Z$ read V_B
» 35, table VI, » » for M_{red} read M_{rad}
» 38, table IX, » » for ipm read cpm
» 39, table X, » » for ipm read cpm
» 45, figure 5, turn the figure clock-wise 90 degrees

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TESTING OF MACHINABILITY BY RADIOACTIVE METHODS

by

Bertil Colding

ACTA POLYTECHNICA NO. 243
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INTRODUCTION

The judging of the economy of cutting tools requires an accurate knowledge of the tool-lives at a great number of combinations of cutting data, work pieces and cutting fluids. As conventional tool-life tests are very expensive to carry out it should therefore be of great importance to work out a method which would enable tool-life measurements to be performed with a good accuracy, in a short time and at low costs.

The most reliable laboratory method of tool-life testing usually consists of machining with a cutting tool, either until complete failure occurs as to HSS tools or to a predetermined amount of flank*) wear is reached as to carbide tools. The latter are usually tested to a wear land of 0.4 to 0.75 mm depending on the hardness or strength of the workpiece. While the wear land versus time curve is not often linear it will often be approximately linear on log-log coordinates. Extrapolations to predetermined flank values are uncertain due to the scatter of the experimental points, especially when the cascading type of wear occurs. However, the scatter of the tool-lives obtained is often great, even if the wear is followed up to the pretermined values because of different tool setting, clearance angel variation, inhomogenous materials a.s.o. These tests require a great deal of time and material and involve considerable cost in order to obtain a relatively small amount of tool-life data.

By introducing the chip-equivalent q Woxén (25, 26) showed as well experimentally as theoretically that q is a basic quantity which together with cutting speed determines tool-life. The chip-equivalent q is defined as the ratio between the total engaged cutting edge length L devided by the chip cross-sectional area A, i.e.

$$q = \frac{L}{A}\,(1/\text{mm}) \tag{1}$$

see Fig. 1, where

$$L \simeq \frac{t - r(1-\sin C_s)}{\cos C_s} + \frac{(90 - C_s)}{180}\cdot\pi\cdot r + \frac{s}{2}\,(\text{mm}) \quad \text{for } t \geq r\cdot(1-\sin C_s)$$

$$A \simeq s \cdot t\ (\text{mm}^2)$$

t = depth of cut (mm), s = feed (mm/r), r = nose radius (mm)

C_s = side cutting edge angle (SCEA)

The relation between cutting speed V and chip-equivalent q in respect to different tool-lives Woxén expressed by the tool-life equation

$$V = \left(\frac{T_*}{T}\right)^n \cdot C \cdot \frac{q + q_o}{1 + c\cdot q} \tag{2}$$

where C q_o and c are constants. T_* is a standard tool-life, e.g. 60 minutes n is the exponent in Taylor's relation VT^n = const.

Being able to use one single variable q instead of s, t, r and C_s and the fact that Eq. (2) is an approximate relation in which the constants can be determined from a rather limited number of tool-life tests, relatively fewer tests are necessary for obtaining tool-life data. However, to establish an accurate relationship between cutting speed and tool-life at only o n e q-value it is

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*) The term "flank" will be used alternatively with "clearance (side)", as well as "face" will be used instead of "rake (side)".

necessary to perform several tests, preferrably totally 9 tests at 3 different speeds, owing to the great scatter of the experimental values.

Many short-time-test-methods have been introduced to reduce time and costs of such determinations but the requirements of good accuracy have had to be reduced still further. The most important of these methods are based upon measurements of the temperature of the tool tip, which is probably the most important factor with regard to tool-life.

The two most common methods for determination of tool temperatures are the well-known thermo-electric: the tool-work and the two-tool methods (12). However, there are some fundamental difficulties associated with the use of thermoelectric data. The emf registered corresponds perhaps to a mean temperature of the cutting edge, and consequently not at all to the temperature on the clearance face, the wear on which is mostly considered the most important one in practical tool-life testing. The chip-tool and work-tool interfaces actually consists of a large number of junctions each of which generates its own thermo-electric emf. These miniature thermocouples are connected in parallel thus giving some sort of an average value depending upon the nature and extent of stray currents that flow between adjacent thermo-electric junctions. Further when built-up materials are present upon the tool face there is no longer a dissimilar pair of metals at the interface.

In order to convert measured values of emf to temperature values, each tool-work combination must be calibrated when using the tool-work method. This is however, not the case with the two-tool method as the composition of the work does not influence the resulting emf. On the other hand the two-tool method seems to fall down on its basic assumption, in that temperatures at the two tools will not usually be the same due to varying coefficients of friction and different thermal conductivities of various tool matherials. For that reason the single tool thermocouple method is generally used, but since calibration curves are inconvenient and difficult to obtain even this test method is limited, especially when many materials do not give suitable calibration curves, sometimes they contain both maxima and minima.

The use of temper colors, which one at a time are smeared on to the clearance or other suitable part of the surface, has given good results (12). As the colors have different temperatures of change it is possible to extrapolate the temperatures to the hottest points of the edge out of the obtained isothermes.

The introduction of speed-change-tests is also a way of attempting to reduce the times of testing. According to the principle of Brandsma (2) a disc is turned from its axial hole towards the exterior which gives a continous increase of cutting speed until the tool breaks down. Large diameters of the discs are here required. Step-wise increase of speed in longitudinal turning have been investigated at KTH in Stockholm (24) on the basis of assumptions of Woxén (27). The method has been proved to be reliable at a suitable choice of speed steps. However, the reduction of costs in relation to conventional tool-life test is relatively insignificant (24).

Besides the methods discussed above there are a number of others which e.g. are based upon type and form of the chips or surface finish. Sometimes these factors are necessary to take into consideration as a complement of other tool-life testing methods.

Use of radioactive methods for studying cutting tool wear was first described in 1951 by Merchant and Krabacher (13, 14) in Cincinnati, Ohio, USA and in 1952 by Colding and Erwall

(5, 6) at KTH in Stockholm. Although the isotopes were produced by irradiating carbide tools by neutrons in atomic piles the independently suggested methods were quite different. In the first, the gamma (γ)-radiation from isotopes Co 60 and Ta 182 (long half lives) was used while in the second the beta (β)-radiation or γ-radiation from isotope W 187 (short half life) was used. The γ-radiation method measures the total wear from the two faces of the tool. The β-radiation method permits studying separately the material transfer from the rake face as well as from the clearance face of the tool. This method also gives absolute values of the wear rate.

Recent Russian papers (11, 16) describe results using the β - and γ -radiation methods, while Hake (10) has applied the γ-radiation technique in some interesting tool wear studies conducted in the Institute for Machine Tool Research at Aachen, Germany.

When a carbide tool wears preliminary experiments showed that essentially all of the tool particles become attached to either the face of the chip that rubs on the rake face of the tool, or to the newly developed surface. Thus, in Fig. 2 the particles coming from the rake face of the tool become attached to surface A of the chip while those particles that leave the clearance face of the tool are welded to surface B. Upon making a second cut, it is evident that the chips produced will have tool wear particles attached to both the shiny and dull surfaces. These particles attached to the shiny surface are associated with rake (tool face) wear while those found on the dull surface are due to clearance (flank) wear.

1. CHOICE OF ISOTOPES

The following general points have to be considered in radioactive work:

1. The isotope must be formed in sufficient amount during irradiation.
2. The isotope must emit radiation suitable for detection.
3. The isotope must have a half-life long enough to allow for transportation from the pile and machining tests.
4. The half-life should, on the other hand, be short enough to minimize the need for handling precautions.
5. If possible, the isotope should be a pure beta emitter to avoid the health hazards involved in gamma emission.

In an attempt to comply with above general considerations regard a carbide cutting tool with a nominal chemical composition of say 80 % WC, 10 % Co, 8 % TiC and 2 % TaC. The resulting isotopes produced after irradiation are W 187, W 185, Co 60, Ta 182. Table 1 shows the half-life and type and energy of each type of radiation produced. The energy is given in million electron volts, (MeV) (1 MeV = 1.6×10^{-6} erg). The half-life $T_{\frac{1}{2}}$ is a very important quantity since it determines the time available for radioactive experiments. If the intensity of radiation (activity at time $\tau = 0$ is called I_o then the activity at any time τ is given by

$$I = I_o e^{-\frac{0.693 \cdot \tau}{T_{\frac{1}{2}}}} \tag{3}$$

When a tool tip is subjected to neutron bombardment, two rates of change are involved. The number of activated atoms increases uniformly with time and the atoms already activated decay. At the end of an infinite period of time the material will be saturated with regard to activation and the activity may be represented by I_∞. For any time of bombardment less than infinity the activity pertaining will be (making use of Equation 3 for the decay component)

$$I = I_\infty (1 - e^{-\frac{0.693 \cdot \tau}{T_{\frac{1}{2}}}}) \tag{4}$$

It is customary to express activity in terms of the curie, C, (1 curie equals a source of strength such that $3.7 \cdot 10^{10}$ atoms disintegrate per second) or the millicurie (mC), which is 1/1000 part of a curie.

Specific activity (S) is the activity per gram of material. When a gram of substance has been saturated with regard to activity its specific activity S_∞ may be expressed as follows

$$S_\infty = \frac{0.6\ F \cdot \sigma}{3.7 \cdot 10^{10} \cdot A} \tag{5}$$

where F is the neutron beam intensity in neutrons/cm^2 · sec.

σ is the cross sectional area of the nucleus of a single atom in barn (where one barn is 10^{-24} cm^2)

A is the atomic weight of the element.

The specific activity (S) after irradiation for a finite time (τ) may be expressed as follows from equations 4 and 5

$$S = \frac{0.6\ F \cdot \sigma}{3.7 \cdot 10^{10} \cdot A} \left(1 - e^{\frac{-0.693\,\tau}{T_{\frac{1}{2}}}}\right) c/g \tag{6}$$

Consider bombardment of above mentioned tool in a neutron flux of 10^{12} n/cm^2 · sec for 1 hour and 1 week duration respectively. With the half-life of the isotopes in Table 1 and their cross sectional areas taken from the litterature (17) Equation 6 yields the specific activities to be expected. In Table 2 are presented the specific activities so obtained and also the total activities expressed in mC per gram tool material. As specific activities of the order of magnitude of 5 - 25 mC/g are desired in this type of work, it is seen from Table 2 that the activity of W 187 will initially be too intense when irradiated 1 week. If, however, the irradiated specimen is set aside for about two weeks, the intensity of irradiation from the W 187 isotope will have decreased to a negligible value and the Co 60, Ta 182 and W 185 isotopes will be available for making β -measurements and the Co 60 and Ta 182 isotopes for γ -measurements. Due to the long half-life of these isotopes measurements can be made for a few days considering the activity as a constant.

When a specimen is irradiated for but one hour, all but the W 187 isotope will have a negligible intensity of radiation. However, due to the short half-life of this isotope it is necessary to make all measurements quickly and to correct for the continuous change in intensity of radiation. The intensity will fall to essentially zero in a period of about 10 days in this case, which is a distinct advantage from the safety point of view. By waiting this length of time all chips may be handled and disposed of in the ordinary manner. When Co 60 is used as the tracer on the other hand, it is not safe to handle chips in the usual manner for a period of years.

Most nuclear particles can possess a rather wide range of energy (i.e., from about 0.05 to 5 MeV). Beta-rays (β) which are rays of particles having the negligible mass of the electron are easily stopped. The range of penetration of such rays into a material of thickness d depends on their energy and upon the density of the material ρ . An approximate empirical expression for β -ray penetration is the following:

$$d\rho = 0.54\ E_M - 0.16 \tag{7}$$

where d is in cm

ρ is in gm/cm^3

E_M is the maximum energy of any particle in the β -ray in MeV, for example, to stop a 1 MeV β -ray would require 1.5 mm (.060 inch) of aluminum or 0.25 mm (.010 inch) of gold.

Gamma ray (γ) absorption follows the law

$$I = I_0 \cdot e^{-\mu d} \tag{8}$$

where μ = the absorption coefficient of the material absorbing the ray, which in turn is proportional to density.

d = the thickness of the absorbing material.

The uncharged particles of a γ -ray are not counted directly in a Geiger Muller tube but they ionize the air in the tube and the secondary electrons thus emitted are detected. Since the degree of ionization in a detecting tube increases inversely with the speed of the γ particles, it is advantageous to use relatively thicker windows in such tubes than would be used for β -rays detection.

It is thus seen that either a method involving the long lived isotopes Co 60, Ta 182, W 185 or the short lived W 187 for β or/and γ measurements will satisfy the requirements 1-5 stated above. Work with the first mentioned isotopes involves a longer time of irradiation (a week (10) to two months (14) have been reported) hence greater cost, greater delay in getting tools ready for use, and greater inconvenience in handling due to the longer half life involved. However, the fact that the activity of the isotopes used remains constant throughout a long range test provides a distinct advantage over the latter method.

The possibility of structural changes in the carbides is assumed to be negligible at this low neutron dose (4). However prolonged bombardment in a high flux of fast neutrons may be assumed to cause certain changes in the crystal structure and thus in the mechanical properties of carbide tools. In this case the irradiation takes place in the thermal shield of the pile, where the flux of fast neutrons is low.

2. EXPERIMENTAL EQUIPMENT AND METHODS

The radioactive methods used in this research work deal with the β-method and the γ-method based upon very short irradiations of carbide blanks making use of the characteristics of the tungsten isotope W 187 only. The main part of this work which deals with turning tests only was performed at KTH (Royal Institute of Technology), Stockholm, Sweden beginning in May, 1952 and ending in December, 1954 (7). Investigations of more or less routine character were also carried out at Massachusetts Institute of Technology (MIT), USA, in the summer 1954 and in 1956-1957, most of the results of which are reported here. The measurements of the chips were all made by Geiger-Muller tubes. The carbide tools were irradiated at the Atomic Energy Research Establishment, Harwell, England and at the Brookhaven National Laboratory, Long Island, N. Y. Since 1955 irradiations for this type of work at KTH are carried out by the Swedish Atomic Energy Commission Pile at KTH, Stockholm.

a) Machining Procedure and Cutting Data

The tools used were all of the clamped type. Figure 3 a shows a carbide blank used at KTH providing four cutting edges and Figure 3 b the tool and holder used at MIT which makes eight edges available for tests. The tools were each subjected to a neutron flux of from 10^{10} - $2.6 \cdot 10^{12}$ neutrons/$cm^2 \cdot$ sec for periods varying between 1 week to 20 minutes and arrived to the cutting laboratory in question one day after irradiation was completed. To some tools a small particle (20 - 50 mg) of carbide was afixed by means of plastic tape. By irradiating tool and particle simultaneously both were believed to obtain the same specific activity. The particle was then used for estimating the absolute wear rate, by a procedure to be described later.

The mounting of the radioactive tools was done by remote handling control shown in Figure 4. The turning tests were carried out in the normal manner except that the blanks were handled by remote control and the operator was protected by a radiation shield mounted on the bed of the lathe as shown in Figure 5, where one also notices an exhaust tube mounted above the cutting tool which was used in most cases together with a fan of 200 to 300 ft.^{3}/min capacity to discharge air from the vicinity of the tool (9). The lathe operator was supplied with film badges and wore gloves and goggles at all times.

Chips were then collected at suitable time intervals, simply by keeping a box below the tool.

The investigations were performed with two Swedish carbide grades when cutting 0.6 % C-steel and Cr-Ni-steel and with the American carbide K2 S cutting AISI 1045 and AISI 4340 steel and TiC 130 AM. Table III shows cutting conditions and materials used.

b) β-measurements

The chips collected for each test were broken into small pieces. They were placed in a box and shaked to be selected at random to form a fixed area within a square or a circle on a Perspex

disc or paper disc (Figure 6). The chip sample was then placed with either side up under the end window Geiger Muller tube for counting as seen in Figure 7. The β-rays are so easily stopped that only those coming from the upper surface have any influence on the registration of radiation be the detector. The weight of each ship sample or the dimensions of the chips were also measured for reasons to be dealt with later.

The irradiated chip of carbide afixed to the tool was dissolved in molten sodium nitrate. The tungstate obtained was then dissolved in water and 1/2000 of the solution evaporated on an iron disc with the same area and bottom thickness as the chips, thus making backscattering corrections unnecessary. The activity of this reference source was measured under identical geometrical arrangements as of the chip samples. The absolute amount of material transferred to each side of the chips was then calculated following a procedure given in Chapter 3 a.

The specific activity of the carbide tools can also be calculated and compared with the reference measurements by using Equation 6, if the efficiency of counting is known. The half-life of the reference sources was measured on several occasions giving figures very close to the accepted value of 24.1 hours (7).

c) γ-measurements

The total activity from both sides of the chips was measured with a gamma ray Geiger Muller tube placed axially in a double cylinder. Approximately 250 g of chips was put between the cylinder walls as shown in Fig. 8. The γ-rays have a great penetrating power so that radiation from both sides of the chips will be effective rays when hitting the tube. The β-rays however, are easily absorbed by the chips and the tube wall.

It should be noted that β- and γ-measurements were carried out simultaneously for all test conditions for the Cr-Ni-material used and in some tests for the 0.60 % C-steel.

d) Microscopic Examinations of Flank and Face Wear

In order to provide a fair comparison between the radioactive techniques and the conventional wear land method a photographic technique was developed enabling one to take photographs of the flank and the face of the radioactive tools at regular intervals of the tests. As such a comparison would be of value only in connection with radioactive tests where the wear was studied until the life of the tool or greater part of it was reached, separate tool-life tests with non radioactive tools were also carried out to yield conventional tool-life curves.

Photographs were taken through a microscope yielding a magnification of about 5 x. The negatives were then examined at 20 x magnification in a profile projector giving a total magnification of about 100 x. The important dimensions measured are seen in Fig. 9, where the edge is stoned according to edge type II, compare Figure 11. The dimension (F) has to be measured when built-up edge conceals the exact start of the wear (the upper part of V_B).

e) Autoradiographic Studies

The distribution of carbide transferred to the chips and to the work piece was studied by means of autoradiography making use of the γ-radiation of W 187. Chips were placed tight

between two commercial X-ray films, while X-ray films were wrapped around the work piece. Experience showed that 50-200 cpm · hr/mm^2 gives reasonable autoradiographs. This means that a chip of an activity of 20 cpm per mm^2 chip area should be exposed for 4-10 hours while e.g. an activity of 0.5 cpm/mm^2 never gives any blackening of the film. It was found that about 2 days of exposure was the limiting time to yield autoradiographs, due to the short half-life of W 187.

f) Activity Measurements

By counting each sample a certain number of minutes, the average number of counts per minute (cpm) may be established. The background count (N_0) determined with no specimen present was then determined and subtracted. The background count normally amounted to from 20 to 22 cpm.

The data of Table IV illustrate the procedure followed, where 5 independent determinations on 5 different samples of a given test are recorded.

The background count (N_0) was in this case 20 cpm over the entire period of time. The value (I_A) are for the activity of the specimen referred to a standard time and are obtained by projecting the measured values of (I) backward in time to a standard time, by use of a curve of activity versus time. The time of measuring (4 minutes in this case) is determined such that the variation due to statistical fluctuation of the radiation is less than $\pm 5\%$ for the entire determination. Since the fluctuation in β or γ emission satisfies a Poisson distribution, the uncertainty may be found by dividing the square root of the number of counts by the measuring time. Thus, for the first value of Table IV the uncertainty will be $\frac{\sqrt{1008}}{4} = \pm 8$ cpm, which is $\frac{\pm 8}{252}$ or $\pm 3\%$. If this value were larger than 5 %, then a longer counting time would be necessary. The background measurement should be determined over a period of about an hour (for background count of about 20 cpm) as may be seen from the following calculation.

$$N_0 = 20 \pm \frac{\sqrt{1200}}{60} = 20 \pm 0.6 \text{ cpm}$$

This corresponds to an uncertainty of $\pm 3\%$.

A plot to be used in making the corrections to (I_A) is prepared by use of Equation (9) which follows directly from Equation 3

$$I_A = (I - N_0)\ e^{-\frac{.693\,\tau}{T_{1/2}}} \tag{9}$$

The value to be substituted for ($T_{1/2}$) here is that for W 187 which is 24.1 hr.

3. DETERMINATION OF ABSOLUTE WEAR RATE AND TOOL LIFE

a) β-measurements

Experiments showed that the relation between the area of chips placed on the measuring disc and the counting rate for the particular arrangement used is a linear function (7), provided the range of areas used is within 200-400 mm^2. The effect of small changes of the distance between chips and window of the GM-tube is negligible provided the variations are smaller than 0.5 to 1 mm. However, it is also important that the distance between disc and end window is not too short as the efficiency of the tube is very sensitive to specimen distance at very small distances of the order of magnitude of 2 to 3 mm. This is seen by Figure 10. where the relative efficiency of counting ($(\eta_\beta)_{rel}$ is plotted versus distance.

The following quantities are associated with the determination of the rate of wear.

I_r = activity of reference source at standard time, cpm
i_r = reference activity, cpm/μg
m = weight of carbide reference particle, mg
M = weight of carbide on chip, mg
Z = time required to wear away one mg of tool material from rake face of tool (Z_R) or from clearance face of tool (Z_C), min/mg
τ = cutting time for wearing away (M) mg from tool, min
I_A = activity of chip sample at standard time, cpm
l = total length of chips in a sample, mm
b = mean width of chips, mm
d = mean thickness of chips, mm
W = weight of chips, g
ρ = density of chips, g/cm^3
v = cutting speed, m/min
s = feed mm/rev
t = depth of cut, mm
r_c = cutting ratio

The activity of the reference source (i_r), expressed in cpm per μg carbide, is related to the measured activity converted to standard time (I_r) as follows.

$$i_r = \frac{2000}{m} \cdot I_r \cdot 10^{-3} \text{ cpm/g} \qquad (7)$$

where (m) is the weight of the carbide particle in mg.

In order to calculate the rate of wear one can either base a formula upon measured weight of each chip sample or upon measured chip dimensions. The derivation in the first mentioned case is given below.

It is immediately evident that

$$Z = \frac{\tau}{M} \text{ min/mg} \tag{8}$$

and

$$M = \frac{I_A}{i_r} \cdot 10^{-3} \text{ mg} \tag{9}$$

therefore

$$Z = \frac{\tau \cdot i_r}{I_A} \cdot 10^3 \text{ min/mg} \tag{10}$$

From continuity considerations

$$W = \rho \cdot V \cdot s \cdot t \cdot \tau \text{ gram} \tag{11}$$

Eliminating τ between this equation and equation 10 have

$$Z = \frac{i_r}{I_A} \cdot \frac{W}{\rho \text{ vst}} \cdot 10^3 \text{ min/g} \tag{12}$$

In applying this equation, (i_r) is determined as previously described, while W and I_A are the average values for each test series.

Alternatively it can be shown

$$Z = \frac{i_r}{I_A} \cdot \frac{1}{r_c \cdot v} \text{ min/mg} \tag{13}$$

In deriving equation 13 it is found that the mean width of the chips (b) is of no importance. Observe also in this connection that the chip sample activity (I_A) should not be corrected back to the standard a r e a in neither equation (12) nor equation (13).

The cutting ratio (chip thickness ratio) (r_c) is determined from

$$r_c = \frac{s \cdot \cos C_s}{d} \tag{14}$$

where ($s \cdot \cos C_s$) is the chip thickness before removal of the chip, and (d) is the measured thickness after the plastic deformation of the chip. Special attention was given to the accuracy of determing (r_c) from equation 14. As the cutting ratio can be determined in different ways equation 14 was therefore tested according to other methods and it was found to be a reliable function (7).

To determine the tool life (T) corresponding to the wear rate (Z) one naturally chooses a certain amount of wear (μ) mg material worn away from the clearance of the tool. The clearance face is taken here to associate with the conventional wear land criterion on the clearance face. If the density of the tool material is (δ), the length of the worn section (L = engaged cutting edge length) and (a) is the cross sectional area of worn away material measured perpendicular to the edge (a = ABC in Fig. 16), then

$$\delta \cdot a \cdot L = \mu$$

or

$$\delta \cdot a \cdot L^x = \mu^x$$

assuming the same shape of the "worn cross section" (a) after a tool has cut to reach a certain wear land (V_B) under two identical conditions except for the lengths (L) and (L^x): The weight μ^x is here a standard which is related to the length (L) in the following way

$$\mu = \mu^x \cdot \frac{L}{L^x} \tag{15}$$

Making use of equation 8 with μ = M and equations 12 and 13

$$T = \frac{\mu^x}{L^x} \cdot \frac{i_r}{I_A} \cdot \frac{W}{\rho} \cdot \frac{q}{v} \cdot 10^3 \text{ min} \quad (16)$$

or

$$T = \frac{\mu^x}{L^x} \cdot \frac{i_r}{I_A} \cdot \frac{1}{r_c} \cdot \frac{L}{v} \text{ min} \quad (17)$$

where the chip equivalent (q) is introduced in equation 16 as a matter of convenience.

γ-measurements

In order to make possible a computation of the tool life corresponding to the sum of rake and clearance wear using the γ-method separate measurements have to be made to establish the ratio of the efficiencies of the β - and the γ-techniques, termed η_β and η_γ. Separate measurements gave a value of η_β of approximately 12 %. The ratio $\eta_\beta : \eta_\gamma$ is calculated by comparing β - and γ-activities from the same test preferrably from the same chips. However, since the γ-measurements have to be done using chip samples weighing about a hundred times the β-samples due to the low efficiency (η_γ) the comparison would thus involve the counting of about one hundred β-samples for each γ-sample. This method of attack would thus be tedious and would only establish the value of η_γ from the present comparison. The efficiency (η_γ) might also be influenced by the slightly varying packing of the chips in the double cylinder. Although separate introductory tests indicated that the way of packing was important one might accomplish several things by studying the $\eta_\beta : \eta_\gamma$ ratio for very different cutting data using the technique of picking out chips for β-measurements at random among the γ-samples. Naturally the degree of packing should be kept as constant as possible independent of the chip type. If then the ratio $\eta_\beta : \eta_\gamma$ was constant for all test conditions one would not only get the ratio desired but also a verification of the agreement between the β - and the γ-methods. It is immediately evident, as the activities are proportional to the weight of chips, that

$$I_\beta = \frac{\eta_\beta}{\eta_\gamma} \cdot \frac{W_\beta}{W_\gamma} \cdot I_\gamma \quad (18)$$

where

I_β = sum of the mean activities from β-tests on back and front of chips weighing W_β gram

I_γ = activity of γ-tests from W_γ gram of chips

The efficiency ratios in Table V were obtained using above procedure and Equation 18. Six different cutting speeds and two different carbide qualities were used cutting Cr-Ni-steel with a feed of 0.5 mm/rev and a depth of cut of 2.0 mm. The range of speeds was choosen as to include the region of severe built-up edge formation. The reasonably constant ratio of η_β / η_γ = 228 ± 7 % indicates that both radioactive methods yield about the same accuracy although the amounts of chips used are widely different.

From the known value of $\eta_\beta \simeq 12$ % it is found that the efficiency of γ-counting for the particular set-up used in this investigation is

$\eta_\gamma \simeq 0.053$ %

Substituting the value of (I_β) from equation 18 into equation 16 yields the tool-life (T_γ) corresponding to a total wear of (μ^x) mg tool material when using the γ-method

$$T_\gamma = \frac{\mu^x}{L^x} \cdot \frac{\eta_\gamma}{\eta_\beta} \cdot \frac{i_r}{I_\gamma} \cdot \frac{W_\gamma}{\rho} \cdot \frac{q}{v} \quad (19)$$

4. ON THE CONSTANCY OF THE WEAR RATE

The account of the results obtained and the discussion of these only apply to the two types of wear: flank and face wear. No attempt is therefore made to separate between predominant nose wear and flank wear in general neither is any attempt made to treat the chipping type of wear separately. Although it is necessary to establish how the wear rate of a tool varies with machining time it is also of great importance to compare the course of wear according to the microscopic and the radioactive technique. In a certain number of cases there is obviously of minor value to know the wear rate measured by the γ-method without knowing whether flank or face is predominant. Neither need a certain volume worn off one side of the tool be of primary importance as regards the life of the tool as this volume may have arisen from a great many geometrically possible shapes as measured from cross sections perpendicular to the primary cutting edge.

In the present investigation three different types of edges of the tools were used in order to study and possibly eliminate the initial wear process. Edge type I is essentially a sharp edge, Fig. 11 a. Edge type II in Fig. 11 b has an approximately 0.1 mm wide flat ground at about 45^{o} angle of inclination against the direction of the tangential cutting force (cutting velocity direction). A small flat of about 0.1 mm length in the direction of the tangential cutting force constitutes the third type used, type III, Fig. 11 c. In some cases this flat had to be made as big as 0.4 mm to ensure avoiding the big initial wear, as disclosed by preliminary wear land tests preceding the radioactive tests.

a) Microscopic Examinations of Flank and Face Wear

When studying the mean wear land (V_B) as a function of machining time one observes in general three distinctly different stages of wear, Fig. 12. Curve I and curve II (valid for a higher cutting speed) consist of parts (A) initial wear, (B) normal wear with a parabolic shape of curve (concave towards the time axis) and (C) the period of cathastrophic wear with a curve of steadily increasing curvature (convex downwards). The magnitude and shape of part (A) depends on the shape of the edge (compare types I, II, III in Figure 11), cutting data and materials. Part (C) is rather seldom observed as in most cases one has to run the tests to wear lands well above the wear land criterion e.g. $V_B = 0.6$ mm to discover that part of the curve. However, for those material combinations where tool wear is excessive and also generally when the cutting speed is very high part C may constitute a big portion of the total life of the tool, curve II. Shaw (23) reports that part C only exists just before break down of the tool when using high speed steel as tool material, while it sometimes is a factor to take into account when cutting with carbide tools.

The rather frequent type of wear, often called "cascading wear", is shown in Figure 13, where real data illustrate the mean wear land (V_B) as function of time in Fig. 13 a. Observe that the maximum wear land ($V_{B_{max}}$) occurs in the middle of the wear land during the first three minutes of turning, while $V_{B_{max}}$ wanders over to the nose part of the edge after about 5 minutes and remains so until the tool is regarded worn out. In Fig. 13 b are shown the maximum

length of the crater (K_B) on the rake side (face), the distance between the beginning of the crater and the cutting edge (K_L) and the width of the crater (K_A). It is concluded that cascading wear shows up on rake face as well as on clearance face. The dimension (K_L) is presumably far more important than the length (K_B) as regards break down of the tool.

In order to make possible an analytic treatment of the wear process it was decided to plot wear data in a double logarithmic scale as to linearize the data:

$$V_B = V_{B_1} \cdot \tau^n \tag{20}$$

$$K_B = K_{B_1} \cdot \tau^m \tag{21}$$

In 25 tests out of a total of 31 tests (n) was found to satisfy the condition

$0.5 \leq n \leq 1$

In 3 tests (n) was found to be less than 0.5.

In the three remaining cases (n) was not constant but corresponded to a "cathastrophic" type of wear as of part C in Figure 12. The inclination of the K_B - τ -lines was smaller than that of the wear land curves, the maximum value being $m = 0.29$ but in many cases m was found to be approximately zero. According to Opitz (18) the maximum depth of the crater (K_d) increases linearly with cutting time, so it can be concluded that the crater depth (K_d) is a critical dimension regarding rake wear, and of the same importance as the distance (K_L) in Figure 13 b, while the length of the crater (K_B) is relatively unimportant.

In Figs. 14 and 15 are shown different relations of above types plotted on log-log coordinates. Fig. 14 a is based on the same data as Fig. 13, where edge type I was used, while edge type II was used for Figures 14 b-d, type III was used in Fig. 15. The sharp change of the inclination of the wear land in Fig. 14 d was probably due to the stoning of the edge, compare the radioactive test. The catastrophic wear pattern is shown by Fig. 14 c. The question of how the stoning of the edge affects the magnitude and the geometrical shape of the wear (in a plane perpendicular to the primary cutting edge) is directly associated with the scatter of tool-life data, as initial wear often constitutes a rather big portion of the wear throughout the life of the tool. Numerous tests showed that a type II edge increased the life of the tool, which is seen by the small inclination of the V_B - τ -curve for the first minute of cutting in Fig. 14 d, although this part of the curve is relatively small in the present example. Fig. 14 d also discloses the relatively insignificant error which is committed by measuring ($V_B - x = G$) instead of V_B provided the life criterion is of normal magnitude, e.g. 0.6 mm. The reason for not using a sharp edge (type I) except in only a limited number of cases will be discussed further in connection with the radioactive tests, but one important reason would be to keep the initial wear under control by a stoned 45° inclination edge of approximately constant dimension. At the same instant as a sharp edge makes contact with the work piece it will brake to form a small flat of random size and orientation, thus constituting one of the several factors being responsible for the scatter of tool life data. Fig. 15 shows V_B - τ -curves for four different speeds when edge type III was used. It is seen that except for the lowest speed ($v = 20$ m/min) there is no sharp discountinuity in the curves as was often found for edge type II. The V_B-value corresponding to $V_B = 1$ min (obtained by extrapolation) would be very small of the order of magnitude 5 times smaller than the corresponding values for edge type II. The different initial magnitudes of the wear lands for the edge types II and III disclose the importance of not using sharp edges in order to ameliorate the ac-

curacy of tool life testing. However, the values of the slopes (n), after the initial wear stage is passed, do not seem to be affected by the shape of the edge. So is also the case with the wear rate (Z_C) as measured with the β-method (Chapter 4 b).

Above discussion shows that the wear land as function of time in many cases may be illustrated analytically over the main portion of the tool life by Equation 20. Therefore, one might expect a definite relation between volume wear and wear land (Chapter 4 b). However, in order to derive such a relation, the geometry of a cross section perpendicular to the primary cutting edge such as ABC in Fig. 16 must be investigated. Here the rake angle is assumed to be zero degrees for the sake of simplicity, (α) is the clearance angle, (φ) is the angle between the plane of wear (BC) and the direction of the velocity vector (OC) here called wear angle. Measurements using the SIP universal measuring machine (KTH) and the Pratt & Whitney electro limit gage (MIT) disclose that (BC) measured any place along the width of the wear land perpendicular to the plane of Fig. 16 is practically a straight line. Therefore (BC) can be regarded as the plane of wear corresponding to a mean wear land (V_B). However, it is not permissible to assume that the wear angle (φ) is zero neither that (φ) is independent of time, this will be shown in the following. If (BC) and (B′ C′) are the geometrical positions of the plane of wear at the times (τ) and ($\tau + \Delta\tau$) then it is easily shown:

$$\frac{2}{\delta \cdot V_L} \cdot \frac{\Delta M}{\Delta \tau} = V_B^{\,2} \cdot \frac{\Delta \varphi}{\Delta \tau} + 2\, V_B \frac{\Delta V_B}{\Delta \tau} (\tan \alpha + \tan \varphi) \tag{22}$$

where $\frac{\Delta M}{\Delta \tau} = \frac{1}{Z}$, δ = density of tool material, V_L = width of wear land.

On the other hand, if we write

$$\frac{M}{\delta \cdot V_L} = f\left[\varphi(\tau),\ V_B(\tau),\ \tau\right] \tag{23}$$

then

$$\frac{dM}{d\tau} = \left(\frac{\delta M}{\delta \tau}\right)_{V_B} + \left(\frac{\delta M}{\delta \tau}\right)_{\varphi} - \left(\frac{\delta M}{\delta \tau}\right)_{\varphi, V_B} = \left(\frac{\delta M}{\delta \tau}\right)_{\varphi} + \left(\frac{\delta M}{\delta \tau}\right)_{V_B} \tag{24}$$

as $\left(\frac{\delta M}{\delta \tau}\right)_{\varphi, V_B} = 0$ in the practical case.

Comparing Equations 22 and 24 yields

$$1)\quad \frac{1}{\delta \cdot V_L} \cdot \left(\frac{\delta M}{\delta \tau}\right) = (\tan \alpha + \tan \varphi)\, V_B \cdot \frac{d V_B}{d \tau} \tag{25a}$$

or integrated

$$V_B \sim \tau^{1/2} \tag{25b}$$

for φ = const., $\frac{dM}{d\tau}$ = const.

$$2)\quad \frac{1}{\delta \cdot V_L} \cdot \left(\frac{\delta M}{\delta \tau}\right)_{V_B} = \frac{1}{2} V_B^{\,2} \cdot \frac{d\varphi}{d\tau} \tag{26a}$$

or $\varphi \sim \tau$

(26b)

for V_B = const; $\frac{dM}{d\tau}$ = const.

Comparing Equation (25) with Equation (20) reveals $n = \frac{1}{2}$ when φ = const. According to H. Schallbroch and R. Wallichs (20) the corresponding empirical relationship was found to be valid for a large number of tools and work piece materials, e.g. carbon steels and aluminum alloys.

Opitz (18) states, however, that (n) lies between 0.5 and 1 for carbide tools in accordiance with observations in the present investigation. It has thus been shown that there is no way of revealing the geometry of the cross section ABC from known values of V_B, φ, and $\frac{dM}{d\tau}$ as (φ) is an unknown quantity. The assumption $\varphi = 0$ (parallel layers worn off in the direction of the cutting velocity vector) yields errors between computed and measured volumes worn off the flank amounting to 100 % or more in some cases, although it is permissible to set $\varphi = 0$ in special cases. The question of a direct correspondence between the wear land criterion (V_B) and the radioactive criterion (φ) will be discussed further in Chapter 5 c.

Another interesting fact is desclosed by Eqs. 25 and 26. They may formally be regarded as representing the cascading type of wear. The fact that (V_B) sometimes does not change at all with increased cutting time is seen by Eq. 26 while the increase of (V_B) can be explained by Eq. 25. The reason for the occurance of the cascading wear lies probably in the built-up edge formation. If it is assumed to protect the edge at a certain instance then the wear will be confined to the lower part of the wear land. Then when the built up edge disapperas it seems reasonable to assume that the wear will be concentrated to the upper part of the wear land. Above reasoning does not imply that (Z) is constant, only that (Z) is constant when either Eq. 25 or 26 is valid. To get some idea of the shape of section ABC in Fig. 16 separate measurements of V_B, x and y (Fig. 9) were taken at different stages of wear for edge type II. Although the reading accuracy of the photographic technique was about $\pm$ 0.001 mm, the boundary at (A, B) was rather diffuse, therefore no attempts were made to study the time variation of the wear angle (φ). On the other hand the order of magnitude of the final value of the wear angle was determined. The results indicated a minimum value of (φ) of 0 to 1^o and a maximum value of 18^o. The latter value corresponded to a V_B-value of 0.16 mm obtained after 30 minutes of turning. Three other cutting edges were run for the same cutting conditions. It was found that wear land (V_B) and wear angle (φ) were different for the same time of cutting. In table VI are given the final values of the wear angle (φ) for corresponding wear lands (V_B). However, in most cases two alternate limiting values of (φ) are given in Table VI due to difficulties of observing the exact value. Also the cross sections of the worn clearance face were measured, multiplied by the width (V_L = 3.4 mm) and the density of the tool material (δ = 13.5 g/cm^3), the mass (M_{cross}) so obtained were then compared with the radioactive data (M_{rad}) as seen in Table VI. The agreement between M_{cross} and M_{rad} is pretty good thus constituting a check of both the microscopic and the radioactive measurements.

b) Radioactive Investigations of the Wear Rate

One of the requirements of a rapid tool life test method is that the amount of wear on both the clearance and the rake of a cutting tool should vary with respect to cutting time in a simple and unique way. Preliminary investigations indicated even an approximately linear wear-versus-time-curve as regards both flank and face of the tool, but not until the run-in period was passed. Therefore, in the studies of the constancy of the wear rate the investigations should partly be devoted to the nature of the initial wear and the possibilities of eliminating it and partly to the course of wear during the larger portion of the tool life. Extrapolations of wear curves obtained during a very short time of cutting might give false information no matter when the data were taken throughout the tool life. As an example consider carbide quality 1 in Fig. 17 a and b, as a typical case where a short time test after approximately one minute of turning would yield an erranous result. The high initial wear rate on the rake face was thought to be due to the sharp

edge type used (Edge type I) for the tool quality 1, while the quality 2 which did not show this had a well rounded edge. After deciding that all tests should be run with edges of type II tests showed it was possible to eliminate the high initial rake wear almost completely. On the other hand a great number of wear data out of different cutting conditions showed a marked initial lower wear rate on the clearance during the first minutes of cutting ($\leq$15-20 minutes) than during the larger part of the tool life. Edge type II thus proved to prolong the tool-life on the clearance as well as eliminating excessive initial rake wear. On the other hand edge type II makes it more difficult to base tool life estimates on the clearance on a short time test. Fig. 18 illustrates clearly these circumstances in a long time tool-life test (180 minutes) conducted to a wear land of V_B = 1.5 mm. During the first 15 minutes the clearance wear rate is much lower than during the rest of the tool life while the rake wear rate is constant throughout the life of the tool. Moreover it should be noted that the clearance wear rate (Z_c) is approximately 3 times the rake wear rate (Z_R). When adding the activity values to yield the curves in Figures 17 b and 18 the mean values of two consecutive values were added to make the curves somewhat smoother than would result when adding directly the activity values taken from Table VII in the latter case. It is interesting to observe an activity value of zero corresponding to 130 min as regards the clearance face, see Table VII, while the maximum value is 155 at 135 min, and the accuracy of the mean value is 45.5 $\pm$ 16 %, the latter figure corresponding to a confidence limit of 95 %. The scatter of activity values on the rake face is also rather great $\pm$ 8.4 %. A comparison with the γ-tests simultaneously performed shows a considerable scatter $\pm$ 24 % for a confidence limit of 95 %. This does not indicate that the γ-measurements yield less accuracy than the β-tests, as this fact is probably to a very large extent due to the smaller number of samples (11 γ-samples as opposed to 42 β-samples). The built-up edge formation was strong during this test. In most tests the scatter was not as great as in above case, however. This is shown in Tables IX-XI.

In order to be able to judge the constancy of the wear rate with certainty statistical methods were used, for example the analysis of variance. The confidence limit was fixed to 95 %. Before using the statistical methods the hypothesis of normal distributions had to be tested in each critical case. If the data did not satisfy a normal distribution t-tests or χ-tests were used (1,3). The method of testing "Outlying Observations" (1) was also used to check whether a value like 0 in Tab. VII should be included in the analysis.

The advantage of treating the radioactive data statistically is not only realized by the importance of getting information on the wear process based upon generally accepted statistical laws rather than subjective assumptions. The relative ease with which the data are treated statistically on a calculator instead of plotting the data on a graph should be fully taken into consideration. Naturally the statistical methods do not tell you whether for example the wavy shape of the points in Fig. 20 b is due to a variation of the degree of packing of the chips in the double cylinder, or a variation of the wear rate which is regarded as continous between the points in Fig. 20 b, etc. In such a case only special studies may reveal the actual cause of the waviness.

From the few examples on the wear rate given above in connection with Figures 17, 18 and 20 b, it is evident that the instantaneous wear may vary considerably. In some cases this may make short time tests doubtful to carry out. As an example Table VIII shows results of β- and γ-measurements of chip samples other than those given in Table VII at 80, 100, 140, 160 and 180 minutes of cutting. Comparing the mean activities at above times with the mean values given

in Table VII shows that corresponding data do not fall within the confidence limits. A short time test might therefore yield an appreciable error. A comparison of Tables VII and VIII also tends to show that the wear varies in a cyclic way around a straight line as illustrated in Fig. 18 and 20 b.

Fig. 19 shows one of the many wear curves where it is readily seen that the wear rate is rather constant. The confidence limits are also drawn on the graph. The cutting speed is here so high (tool-life short) that the tool wears in very quickly and therefore the initial wear period is almost absent although edge type II was used. A very interesting curve is shown in Fig. 20 a where the γ-activity of almost all the chips formed during a 9 minute continous cut were measured and the 16 data were added. Three definite discontinuties (steps) are seen, the parts of the curve in between are straight and parallel, the inclination being 55 to 60. This result shows that chipping occurred during the initial wear period. This is not the case, however, during the period between 50 and 57.7 minutes of cutting when again all chips were measured Fig. 20 c. The slope of the curve is here 86. By measuring eleven chip samples collected at suitable time intervals between 20 and 130 minutes of cutting and adding their activities a slope of 87 was measured, Fig. 20 b. This shows that the length of the initial wear period was at least 10 minutes. From Table IX it is also readily seen how important a role the initial wear plays in tool life testing when using a short time test method. The initial wear is gone already after probably 0.5-1 minutes on the rake while it has probably not disappeared until about 10 minutes has elapsed as to the clearance. The γ-measurements as of Table IX do not seem to reveal the initial wear as the small initial wear on the clearance is compensated by a bigger wear on the rake. This latter tendency of edge type II should be remembered. Table X a-f shows the variation of the wear rate with time under 6 different cutting conditions when using Edge type III. Both β - and γ-measurements were carried out. There is a definite tendency for the clearance wear to start out without any initial wear except for the first minute or two. These results are directly comparable with the findings of the microscopic measurements. It should be observed that in these cases the cutting speeds were deliberately chosen low enough to obtain rather long tool-lives, because of the tendency of the initial wear period to be shorter the shorter is the tool-life. Consequently it is more difficult to study initial wear under cutting conditions yielding short tool-lives.

As a further example of the wear rate variation during a long time test clearance and rake wear data from β-tests are given in Table XI showing a constant wear rate on both sides of the tool from 5 minutes to 40 minutes and 1 minute to 40 minutes respectively, when the tool was regarded worn out. The edge was here of type I, but stoned slightly by hand to yield a shape equivalent to type II but of much smaller dimensions. Therefore these data should be directly comparable to those of Fig. 17 for quality 2. Thus only a slight polishing (stoning) of the edge might yield a constant rake wear right from the beginning of cutting. As a further illustration of the latter statement, see Table XII where in a) the wear of the firstly formed chip was studied primarily on the rake. The mean value 444 $\pm$ 36 of the eight measurements of consecutive samples of 10 cm length each is within the limits of the mean value 480 $\pm$ 12 of seven measurements from a chip of 70 cm length taken after a further turning time equivalent to 1 meter chip, see Table XII b. In Table XII c are the results of tests of eleven 10 cm samples taken at random from a bag of chips the weight of which is equivalent to half a minute of turning after a total turning time of 3 minutes. The mean value of 543 $\pm$ 78 is approximately the same as in the previous two cases. These results again emphasize for edge type II the constancy of the wear rate of the rake face right from the start of cutting, while a comparison between Tables XII a, b and c indicates

a lower wear rate at the start for the clearance. The constant wear rate prevails on the rake even for the last cm of chips before the radioactive tool broke down (failed) completely after 6 minutes. This is revealed by Table XII d. It is interesting however, that the flank wear increased from about 120 to about 4400. This result has its parallel one in the so called Schlesinger criterion of failure of a tool as registered by the sudden increase of the feed force (thrust force), while the cutting force in the velocity vector direction remains unchanged (21).

The summing-up of the conclusions regarding the constancy of the wear rate may be made by the following statements.

1. The volume wear rates (Z_C) and (Z_R) are in most cases approximately constant after the tools is worn-in.

2. The wear land (V_B) plotted versus machining time on log log may be approximated by a straight line after the tool is worn-in, provided the wear rate (Z_C) is constant.

3. Catastrophic wear (Figs. 12 - part C and 14 c) means that the wear rate (Z_c) increases with time.

4. Cascading wear on rake and clearance face revealed by microscopic measurements (Fig. 13) is clearly shown by use of the γ-method provided all chips produced are measured (Fig. 20 a).

5. Cascading wear is always present to a larger or smaller extent. This type of wear depends probably on the built-up edge formation and it seems to disappear the higher is the cutting speed. This observation might explain the very constant wear rate observed at high cutting speeds.

6. Initial wear is largly dependent on shape of cutting edge. Edge type I (Fig. 11 a) yields a high initial wear rate on clearance as well as on rake. Edge type II (Fig. 11 b) yields an initial wear rate on the clearance which is lower than after the tool is worn in but eliminates the initial rake wear. Edge type III (Fig. 11 c) tends to eliminate initial clearance wear but not initial rake wear.

5. COMPARISON BETWEEN RADIOACTIVE AND CONVENTIONAL TOOL LIFE CURVES

a) Accuracy of β-and γ-measurements

Due to the use of considerably larger chip samples for γ-measurements than for β-measurements one would expect a greater accuracy of the computed wear rates in the former case. The above discussed constant efficiency ratios of the two methods shown in Table V is an indication of both methods yielding about the same accuracy. In Fig. 21 the wear rates using Eqs. (17) and (19) are plotted versus cutting speed when cutting Cr Ni-steel with carbide quality 2. The wear rate is expressed as the time to wear away a total amount of 1 mg from flank and face of the tool. From Fig. 21 it is readily seen that the accuracy of the two methods are approximately equal. Further comparisons reported in this investigation are given in Tables VII to X which strengthen above statments. In view of all the measurements done in this investigation it appears that the β- or the γ-method gave an accuracy of between $\pm$ 2 % and $\pm$ 20 % (95 % confidence limit) for about 10 measurements.

b) Flank and Face Wear Rate Function of Cutting Speed and Feed

Using Eqs. (12) or (13) the wear rate (Z) – defined by Eq. (8) as the time in minutes to produce one milligram (mg) of wear particles – is plotted versus cutting speed (V) on log-log coordinates as shown by Figures 22 a, b – 28 a, b. Two types of Z-curves can be distinguished, one associated with the wear on the clearance face (Z_C) and one associated with wear on the rake face (Z_R). In Figures 22 c – 25 c are given the corresponding tool-life for a wear land of V_B = 0,6 mm, while the tool life criterion is V_B = 0.030 in. (0.725 mm) in Figures 27 c – 28 c and V_B = 0.015 in. in Fig. 26 c. In the two latter cases also the curves for total destruction (T_d) are given.

Both the Z_C– and Z_R-curves are seen to be similar in appearance to the conventional wear land curves. It is also evident that the Z_C-curves better approximate the wear land curves than the Z_R-curves. The latter curves, however, have a steeper inclination than the former except in the case of the work material being a titanium alloy, Fig. 28, where the opposite is the case. A general feature of most of these curves seems to be the existence of a maximum tool-life. In those cases where this is not shown as in Figures 23 and 25, it is believed that a maximum would have shown up if the test cutting speeds had been choosen lower. Figures 26 and 27 reveal both a minimum and maximum tool-life for each particular feed. In order to check that this form of a tool life curve is possible and is not due to inaccurate measurements or due to pure chance, Figure 29 should be compared with Fig. 26 a for the feed 0.38 mm/rev, both Figures concern turning of AISI 1045 with K2S carbide tools. In Figure 29 are plotted as function of cutting speed the following variables:

u = total cutting energy per unit volume
u_s = shear energy per unit volume
u_f = friction energy along the tool face per unit volume
r_c = chip thickness ratio

μ = coefficient of friction on tool face
ϕ = shear angle

The forces (F_c, F_t) were measured by a MIT-tool dynamometer (8), the chip thickness was measured by micrometer. From these measurements u, u_s, u_f, r_c, μ and ϕ were calculated using Merchant's relation (15). It is seen from the curves plotted in Fig. 28 that there exists a maximum and minimum for the energy curves and the curve of the coefficient of friction. This indicates that the shapes of the curves in Figs. 26 and 27 are correct, although nobody has hitherto found a general law realting tool-life to any of above variables. Moreover the interesting shapes shown by Fig. 26 and 27 are predicted by Shaw (22).

A comparison of the relative rates of wear for the clearance (Z_C) and rake (Z_R) faces is given in Fig. 30. It is seen that in most cases the rate of clearance wear is smaller than the rate of rake wear (i.e., $Z_C/Z_R > 1$) except for intermediate speed regions. The same general pattern of (Z_C/Z_R) versus (V) seems to hold for both AISI 4340 and TiC 130AM as revealed by Fig. 31 a, b. By comparing Figures 30 and 31 a with Figs. 22-27 it is obvious that the ratio Z_C/Z_R) increases (as long as the feed is big enough) with cutting speed (V) in the regions where Taylor's relation ($VT^n = C$) is valid i.e., in the practical machining region. The reverse is true for TiC 130AM, Figs. 28 and 31 b, where it is seen that above ratio decreases with speed. One would therefore expect all materials except for TiC 130AM to fail due to crater formation occuring at high speeds. This is confirmed in those cases where the tools were run until failure. The relatively greater clearance wear for TiC 130AM at higher speeds was found to be due to nose wear in particular, which in fact caused failure.

With the small feed of 0.31 mm/rev. the ratio (Z_C/Z_R) decreases also with increased cutting speed (Fig. 30) in the same way as does TiC 130AM at the three feeds investigated. These observations indicate that if the tool material were more resistant to clearance wear than in the present cases then at still higher speeds the ratio (Z_C/Z_R) would increase even for very small feeds. This reasoning assumes that there exists a limiting feed below which clearance wear will be excessive provided the cutting speed is not reduced considerably.

c) Comparison Between the Accuracy of the β-method and the Wear Land Method

An examination of Figs. 22-28 indicates that there is in general no significant difference between the accuracy of the β- and the wear land method. In the case of the data in Fig. 22 a statistical analysis indicates an accuracy of $\pm$ 8.5 % of the linear protion of Fig. 22 a for (Z_C) vs. (V) for 6 data points but only $\pm$ 33 % for the wear land method for 9 data points in Fig. 22 c. It should be emphasized that many of the wear rate values for the same material combination are based upon short time tests carried out with carbide tools irradiated at different times. Therefore in the present accuracy comparison between the two methods we deal with the absolute radioactive β-method. The tests performed indicate that the exponents of the relations $V \cdot Z_C^{\alpha} = A$ are about the same (compare the values of n, C, α, A in Figs. 22-28). However, it is also found that if a wear land of size V_B = 0.6 mm corresponds to a clearance wear of 1 mg for one particular combination of cutting conditions, the same does not seem to be true for another combination of tool and work materials or for another feed (compare Figs. 22-28). In fact there are indications of more material have to be worn off the clearance face to reach V_B = 0.6 mm, the bigger is the feed. This would either signify that the final value of the wear angle (φ) in Fig. 16 for V_B = 0.6 would increase with feed (7) or excessive nose wear would occur at heavy

feeds. If above reasoning is true then the wear criterion (μ^*) in Eq. (15) would have to be changed according to some function of the feed when evaluating radioactive tool life tests. However, the author does not feel this is necessarily a weakness of the radioactive method as the wear land criterion of e.g. $V_B = 0.6$ is arbitrarily choosen. Similarly it can be argued that in many cases the rake wear is evidently the most important as a tool may fail before a certain wear land is reached owing to crater wear. For some materials Opitz (18) found the ratio of the depth of the crater divided by the distance between the cutting edge and the midpoint of the crater be a significant quantity as regards tool failure.

It is possible on basis of radioactive rake wear data and crater dimensions to arrive at Fig. 32, where above ratio is set = 0.15 corresponding to 3 and 15 mg permissable rake wear for the feeds of 0.5 and 1.0 mm/rev. respectively (7). The tool-life criterion for the feed 0.5 mm/rev was determined from an approximate relation between rake wear volume and above ratio (0.15). Then the tool-life criterion for the feed 1.0 mm/rev was calculated making use of Opitz' proportionality relation between crater width and chip thickness (18). The tool life criterions of 1.5 ($V_B \cong 0.6$) and 4 mg ($V_B \simeq 1.0$ mm) would yield longer tool-lives than reality permits as revealed by Fig. 32 when the cutting speed is too high. The point of intersection of any of the curves corresponds to the speed at which the wear criterion would have to be changed in order to give reliable information concerning the economy of cutting tools. Notice the position of the total destruction curve (T_d) in relation to the curve for $\mu_o = 1.5$ mg in Fig. 32

d) Costs of Radioactive Methods Versus Wear Land Method

A study of the cost quantities of the two methods rêveals that the wear land method has relatively greater costs for work material than for labor and machine (7). The radioactive method requires lower costs for work material, machine and labor than the costs of irradiation, measurements of the chips and radioactive equipment. The tremendous saving of material seems to be the most significant advantage of the radioactive method resulting in appreciably lower total costs than for the wear land method. Also the possibility of obtaining results in a relatively short time should be appreciated. As an example it is worth mentioning that one tool-life curve requires about 1 man hour total time at the lathe and 4 man hours for performing the measurements of the radioactivity of the chips. If absolute values are necessary the calibration procedure described in chapter 2 b has to be carried out which means approximately 3 additional hours, a time which of course is reduced in relation to the number of tool-life curves wanted per irradiation. Above tool-life curve is considered to be based upon four to six tests at different cutting speeds.

6. SPECIAL STUDIES

a) Autoradiographic Studies of the Distribution of Wear Particles on Chip and Work

The distribution of tool material transfer to the chips was studied by means of autoradiography (Chapter 2 e). However, due to the relatively lower activity of the side of the chips corresponding to the clearance face than that of the rake those autoradiographs were not succesful. So the autoradiographs shown in Figures 33-38 correspond to wear distribution of rake wear. Fig. 33-35 represent the wear distributions for the cutting speeds V = 9, 87 and 137 m/min when cutting AISI 1045 with K2S carbide at a feed of s = 0.26 mm/rev and a depth of cut of t = 1.5 mm. Fig. 36, 37, 38 show the wear distribution at V = 9, s = 0.38, t = 1.5 for AISI 1045 vs. K2S, at V = 100, s = 0.5, t = 2 for 0.60 % Carbon steel vs. carbide and at V = 100, s = 0.5, t = 2 for CrNi-steel vs. carbide respectively. Any general conslusions concerning the wear distribution for the different material combinations investigated cannot be drawn from the rather limited test material. It is seen from the Figs. 33-38 that the material transfer may be fairly even or very discontinous. Fig. 39 shows an interesting case where a small piece of the tool material had broken off and cut a groove in the chip, where it finally stuck. The size of this piece, estimated from the activity, was 15 μg.

From Fig. 40 it is seen that the material transfer to the work piece is distributed partly evenly (the faint lines) and partly discontinously (the black spots). This region of spots and marked lines corresponds to start or finish of a cut. It should be mentioned that there are possibilities of estimating the weight of the transfer, two of which are suggested by Rabinowicz (19).

b) Accuracy of Absolute Measurements of Wear Rate

The accuracy of the absolute measurements of the wear rate described in Chapter 2 b and 3 a is a very important question as the ideal case of comparable wear rates figures established out of different irradiations but under the same cutting conditions, will eliminate the necessity of having some kind of standard machining tests against which all activity measurements have to be checked. The evaporated carbide layers on the bottom of the disc previously described is in most cases found not to be even which might mean that self absorption plays an important roll. However, measurements on carbide solutions from the same irradiation are seen to be within ± 1 % of each other in spite of a somewhat uneven layer of solution, shown by Table XIII, where such measurements are tabulated from three different irradiations. The small influence of the thickness of the solution or the self absorption within the specimens is confirmed by Table XIV, where are shown the reference acitivites (i_r) corresponding to three different weights (greatest weight ratio is roughly 3.5) of the carbide pieces fastened to three tool blanks which were irradiated in the same container.

Also the fact that many of the results obtained for the same material combination work – tool are based upon reference activities which were calculated from different irradiations sometimes several months apart, emphasize the good accuracy of the absolute measurements of the wear rate.

c) Radiation Dosages Received

The maximum amount of radiation received by anyone who was involved in the present investigation amounted to 0.250 roentgen per week on the wrist. This is about 1/4 of the stated permissible dosage per week for continous radioactive work. The experience showed that if the present method is to be used regularly during the year, i.e. more than 150-200 hours of work per year, more rigorous shielding equipment is necessary when mounting the carbide tips (see Figure 4). Otherwise the protection of the present set-up is good enough. For example the operator of the lathe need only watch the tool when engaging the depth of cut besides the mounting of the tool.

The contamination of the air has proved to be very small. Measurements of the activity of air samples taken 30 cm from the cutting edge showed that if all the radioactive dust resulting from the cutting would concentrate at the same place (30 cm from the cutting edge) the total activity would be $0.7 \cdot 10^{-7}$ $\mu C/m^3$, while the maximum permissible dosage is $3 \cdot 10^{-7}$ $\mu C/cm^3$.

In some cases the weights of the carbide tips were measured before and after turning and compared with the calculated values (7). The agreement was reasonably good. In view of Merchant's statement (14) of only finding 4.2 % of the total activity in the cutting fluid used and of the measurements made in this investigation it is concluded that a very large percentage of the total wear of a tool is to be found on the chips, a small amount on the work piece and a still smaller amount is in the athmosphere.

7. SUMMARY

A large number of machinability tests were carried out on five different work materials using radioactive carbide cutting tools. The tests were made in an ordinary lathe, provided with radiation shield. The wear on the carbide tools was determined by measurement of the radioactivity of the chips cut.

With one of the methods, the β-method, the β-radiation from small quantities of chips of the order of 1 g per measurement sample are measured by GM-tubes of the end window type. The β-method enables separate measurement to be made of the wear on the clearance and the rake side of the tool.

The other method, the γ-method, measures the total activity from both sides of the chips by means of a thick walled GM-tube, placed longitudinally in a double cylinder holding app. 250 g chips.

Only the radiation from the isotope W187 (half-life 24.1 h) was employed, produced by neutron irradiation in a reactor generally with 10-20 $\cdot$ 10^{11} n/cm^2 $\cdot$ s for 1 hour, making the specific activity 25-50 mC/g.

The rate of wear was approximately constant up to the wearing out of the tool, after a rather brief period of running-in had gone, so that the mean activity in the chips produced during a few minutes' turning constitutes a relative measurement of the rate of wear. By means of reference measurements on a carbide chip dissolved in $NaNO_2$ and the cutting data used, absolute values of the tool-lives were obtained.

These two radioactive methods give approximately the same degree of accuracy, i.e. varying between $\pm$ 2 % and $\pm$ 20 % for about 10 measurements. The dispersion of the tool-lives was smaller with the radioactive methods than with the conventional tool wear method in some cases while of the same order of magnitude in the remaining cases.

The total cost of test for a tool-life curve using the radioactive method is appreciably lower than the corresponding cost with the conventional method.

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TABLES

Table I

Half-life and energy of isotopes produced by neutron bombardment of a carbide tool

Isotope	Half-Life	β-energy MeV	γ-energy MeV
Co 60	5.3 years	0.306	1.17, 1.33
Ta 182	115 days	0.5	1.13, 1.22
W185	73 days	0.68, 0.48	
W187	24.1 hours	1.33, 0.63	0.78, 0.686, 0.552
			0.46, 0.134, 0.072

Table II

Specific activity and total activity after 1 hour's and 1 week's irradiation

Isotope	1 hour		1 week	
	S mC/g	Tot. A. mC	S mC/g	Tot. A. mC
Co 60	0.4	0.04	14.5	1.45
Ta 182	1.5	0.03	52	1.04
W185	0.075	0.06	2.7	2.2
W187	25.0	20.0	900	720
Total		20.13		724.51

Table IV

Illustration of the procedure to calculate the chip activity (I_A) referred to standard time

Time	Counts	Counting time, Min.	I cpm	I-N cpm°	I_A cpm
13.00	1008	4	252	232	464
13.05	1220	4	305	285	570
13.10	1120	4	280	260	525
13.15	1152	4	288	268	544
13.20	1180	4	295	275	562

$I_A = 533$

Table III

Machining and material data

Work piece materials:

0.6 % C, 0.8-1.1 % Mn, 0.20-0.24 % Si, max. 0.04 % S, max. 0.04 % P

0.39 % C, 1.1 % Mn, 0.27 % Si, 0.02 % S, 0.01 % P, 1.38 % Ni, 0.20 % Mo

AISI 1045, AISI 4340 steel and TiC 130 AM titanium

Tool materials:

Grade 1: 7 % Co, 3 % TiC, 3 % TaC, 87 WC
" 2: 8.5 % Co, 4.5 % TiC, 87 WC
" K2S:

Tool geometry:*)

As to grade 1 and 2:
$\alpha_b = 0^o$, $\alpha_s = 7^o$, $\phi_e = 7^o$, $\phi_s = 7^o$, $C_e = 45^o$, $C_s = 45^o$
$r_n = 0.04''$
As to K2 S:
0^o, 6^o, 6^o, 6^o, 15^o, 15^o, 0.015" vs. AISI 1045
-7^o, -7^o, 7^o, 7^o, 15^o, 15^o, 0.032" vs. AISI 4340 and TiC 130 AM

Cutting data:

$9 \leq V \leq 166$ m/min $0.13 \leq t \leq 1.0$ mm/r $1.5 \leq b \leq 3.0$ mm

*) American Standards Association Nomenclature

Table V

Ratio of counting efficiencies ($\eta_\beta : \eta_\gamma$) per g of chips when cutting CrNi steel with carbide grades 1 and 2

Cutting speed m/min	Efficiency ratio
100	223 258 248 243
85	198
80	209 232 225 220 153 262
60	217 265
50	222
40	242
Average (for a confidence limit of 95 per cent)	228 ± 16
Uncertainty	± 7 per cent

Table VI

Comparison between wear land (V_B), wear angle (φ) and amount of material worn off the clearance face

Grade vs. work	V	s	t	V_BZ	φ^o	M_{cross} μg	M_{red} μg
1 vs. 0.60 % C	100	0.5	2	0.6	0.4	-	-
2 vs. 0.60 % C	100	0.5	2	0.6	1.3	-	-
2 vs. CrNi	100	0.5	2	0.07 0.21 0.21	3.0 2.3 5.7	44.1 86.3 168.5	47.2 ± 2.1 137 ± 26
2 vs. CrNi	80	0.5	2	0.11 0.335 0.335	0 1.0 3.0	34.9 294 409	35.9 ± 4.7 516 ± 205
2 vs. CrNi	80	0.5	2	0.10 0.16 0.16	1.0 9.6 18.0	33.1 186 228	35.7 ± 4.6 236 ± 60
2 vs. CrNi	80	0.5	2	0.10 0.63	0 1.0	20.2 762	40.6 ± 3.9 1400 ± 460
2 vs. CrNi	80	0.5	2	0.09	4.6	36.7	41.2 ± 5.7
2 vs. CrNi	60	0.5	2	0.20 0.38 0.38	4.0 1.3 3.8	125 452 543	118 ± 15 424 ± 82
2 vs. CrNi	60	0.5	2	0.33 0.33	0 3.2	239 412	462 ± 101
K2 S vs. 4340	75	0.26	2.5	0.675	0.5	-	-
K2 S vs. 4340	120	0.26	2.5	0.60	0	-	-

Table VII

Instantaneous β - and γ-activities at different stages of machining between 1 min. to 180 min. Carbide quality 2 vs. 0.6 % C-steel. Edge type II. V = 50, s = 0.5, t = 2. The cutting time 180 min. corresponds to V_B = 1.5 mm (compare Fig. 18)

β - test			γ-test	
Time min	Rake cpm	Clear cpm	Time min	cpm
1	94	60		
2	107	61	2	116
3	38	61		
4	93	84		
5	26	62		
6	43	84	6	100
9	35	106		
12	31	95		
15	21	96	20	123
20	27	107		
25	17	131		
30	64	133		
35	74	126		
40	30	154	40	152
45	29	111		
50	34	149		
55	32	188		
60	18	145	60	132
65	29	151		
70	34	115		
75	15	141		
80	20	98	80	48
85	49	190		
90	34	180		
95	22	138		
100	20	135	100	242
105	17	133		
110	42	158		
115	54	218		
120	29	128	120	58
125	35	134		
130	0	98		
135	155	145		
140	32	115	140	183
145	25	143		
150	43	120		
155	79	146		
160	17	71	160	236
165	53	142		
170	77	(418)		
175	61	257		
180	22	102	180	232
Mean	45.5 ± 16 %	145 ± 8.4 %		148 ± 24 %

Weight of samples 66.4 g.

Table VIII

For same conditions as in Table VII, several samples from continous chips measured at some different stages of wear

β-test			γ-test	
Time min	Rake cpm	Clear cpm	Time cpm	cpm
		108		
		89		
80	22	85		
		100		
		98 ± 20 %		
		122		
		119		282
		109		261
140	32	114	100	242
		122		256
		104		230
		111		252 ± 8 %
		118		
		115 ± 10 %		
	13	63		
160	18	67		
		74		
	15.5	71 ± 40 %		
	114 ± 9 %	420 ± 3 %		
180	94 ± 7 %	492 ± 3 %		
	24 ± 12 %	102 ± 8 %		

Table IX

The variation of the activity on rake and clearance for the first minute of turning compared to the activity for between 10 min and 50 min of turning β- and γ-tests. Carbide quality 2 vs. CrNi-steel. Edge type II.
V = 60, S = 0.5, t = 2

	β-test			γ-test
Time min	Clear cpm	Rake cpm	Clear+Rake cpm	I ipm
0.1	57	410	475	
0.2	45	201	245	
0.3	35	201	236	
0.4	39	194	235	
0.5	41	197	238	
0.6	32	147	179	
0.7	43	385	428	
0.8	32	150	182	
0.9	43	147	190	
1.0	32	132	164	
2	-	-	-	282
3	-	-	-	200
4	-	-	-	226
5	-	-	-	242
10	43	164	207	176
15	51	147	198	221
20	60	140	200	223
25	61	132	193	208
30_1	66	119	185	249
30_2	76	153	229	
35	66	134	200	267
40	91	186	277	284
45	95	100	195	247
50	121	176	297	338
Mean	(0.1-1) 39.9 ± 5.5 (10-50) 73.- ± 16	(0.1-1) 227 ± 74 (10-50) 145 ± 18		(2-50) 243 ± 26

Table X

The variation of the activity with cutting time using edge type III

a) V = 50, s = 1.0, t = 3, Carbide quality 1 vs. CrNi
b) V = 30, s = 1.0, t = 3, Carbide quality 1 vs. CrNi
c) V = 20, s = 1.0, t = 3, Carbide quality 1 vs. CrNi
d) V = 80, S = 0.31, t = 2, Carbide quality 1 vs. CrNi
e) V = 50, s = 0.5, t = 2, Carbide quality 2 vs. CrNi
f) V = 70, s = 0.5, t = 2, Carbide quality 2 vs. CrNi

		β-test			γ-test
	Time min	Clear cpm	Rake cpm	Rake + Clear cpm	I ipm
a)	2	137			711
	5	96			590
	6	143			561
	7	128			628
	8	150			383
	9	141	1410	1551	611
	10	132	1310	1442	612
	Mean	(2-10)130 ± 16	9-10 1360		(2-10)585 ± 92
b)	2	147			667
	5	149			400
	8	110			310
	10	106			334
	11	123			363
	12	130			427
	13	101	606	707	249
	14	127	566	693	297
	Mean	(2-14)125 ± 15	(13-14)586		(2-14)381 ± 108
c)	5	103			126
	10	95			122
	15	147			94
	20	113			124
	25	133			66
	26	133			96
	27	127	123	250	109
	28	125	141	266	151
	Mean	(5-28)120 ± 14.5	(27-28)132		(5-28)111 ± 22
d)	2	213			642
	5	254			553
	8	285			671
	10	342			600
	12	336	237	573	645
	14	328	224	552	540
	Mean	(8-14)325 ± 31	(12-14)230		(2-14)668 ± 43
e)	5	94	76	170	153
	10	83	72	155	124
	15	105	57	162	167
	20_1	84	53.5	137	107
	20_2	72	63	135	
	25_1	69	51	120	143
	25_2	63	47	110	
	Mean	(5-25)81 ± 14	(5-25)59.5 ± 10.1		(5-25)139 ± 29
f)	0	229	852	1081	
	0		795		
	2	103	166	269	275
	5	81	192	273	275
	8	-	-	-	243
	10	81	171	252	229
	15	88	153	241	207
	Mean	(2-15)88 ± 16.5	(2-15)172 ± 26		(8-15)223 ± 33

Table XI

Rake and Clearance wear rate in feet/μg at different stages of machining. Edge type I. K2S carbide vs. AISI 1045 steel.
V = 87, s = 0.26, t = 1.5

Time min	Z_C feet/μg	Z_R feet/μg
1	43.7	7.42
2	55.5	11.5
3_1	69.8	10.5
3_2	98.5	9.89
4	67.8	10.2
5_1	104	9.65
5_2	87.4	9.68
8	71.8	10.25
10_1	57.5	11.1
10_2	62.5	10.8
16_1	29.9	10.8
16_2	34.2	10.9
20	54.2	15.3
24	42.8	11.1
26	44.8	-
28	-	11.3
36	32.6	10.0
38	27.5	10.2
40	32.4	10.0
Mean	(1-5) 75.2 ± 20.5 (8-40) 44.6 ± 10	(1-40) 10.6 ± 0.6

Table XII

The variation of the instantaneous activity along consecutive chip samples

a) from the first chip formed

b) from a chip about 1 meter further away from the last sample of a)

c) from samples taken at random of chips formed after about three min. of cutting

d) from the last chip formed just before tool failed

Edge type II. Carbide quality 1 vs. CrNi.
V = 100, s = 0.5, t = 2.

	Test no	Clear cpm	Rake cpm
a)	1		400
	2	59	383
	3	64	439
	4		463
	5		422
	6		437
	7		479
	8		532
	Mean	61.5	444 ± 36
b)	9	71	550
	10	55	492
	11		499
	12		441
	13		473
	14		470
	15		438
	Mean	63	480 ± 12

	Test no	Clear cpm	Rake cpm
c)	1	154	513
	2	149	717
	3	146	592
	4	148	528
	5	125	634
	6	102	380
	7	92	464
	8	108	392
	9	103	716
	10	117	453
	11	94	582
	Mean	122 ± 16	543 ± 78
d)	1	2090	440
	2	2130	422
	3	4370	756

Table XIII

Accuracy of the determinations of the activities of reference pieces

Irradiation	Specimen no.	Activity cpm
A	1	3730
	2	3570
	3	3740
	4	3595
B	1	2640
	2	2070
	3	2890
	4	2570
C	1	3780
	2	3590
	3	3520
	4	3560
	5	3520
	6	3690

Activity values accurate within ± 1 per cent

Table XIV

Reference activities of three refreence pieces from the same irradiation

Carbide	I_{ref} cpm/μg	Weight of reference piece mg
D	$1.35 \cdot 10^3$	35.96
E	$1.29 \cdot 10^3$	66.47
F	$1.30 \cdot 10^3$	124.17

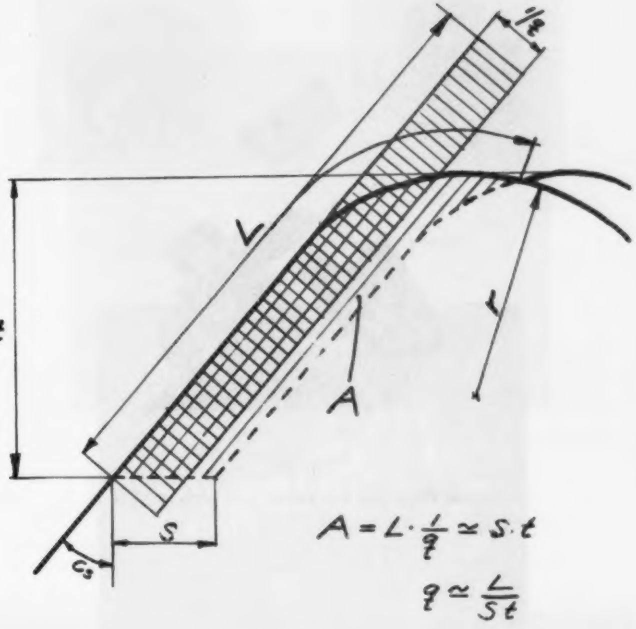

Fig. 1

Definition of chip equivalent

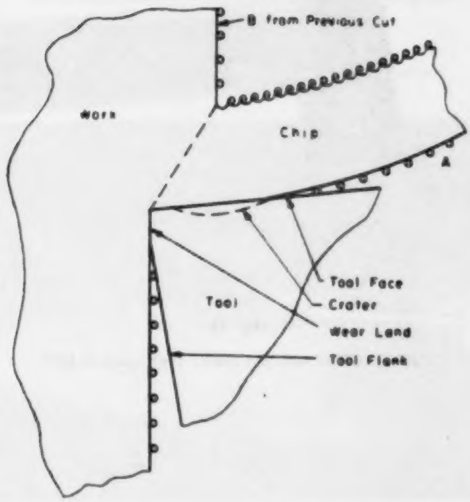

Fig. 2

Transfer of wear particles from flank and face of tool

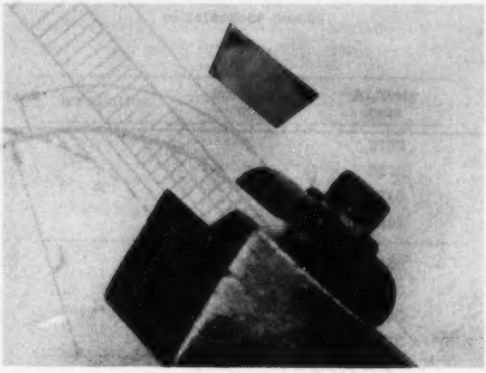

Fig. 3a

Carbide blank and tool shaft, type used at KTH

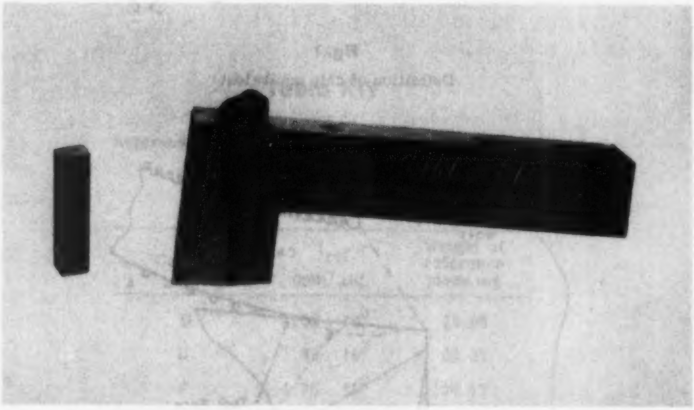

Fig. 3b

Carbide blank and tool shaft, type used at MIT

Fig. 4
Mounting of radioactive carbide blank.

Fig. 5
Lathe with radiation shield and dust extractor

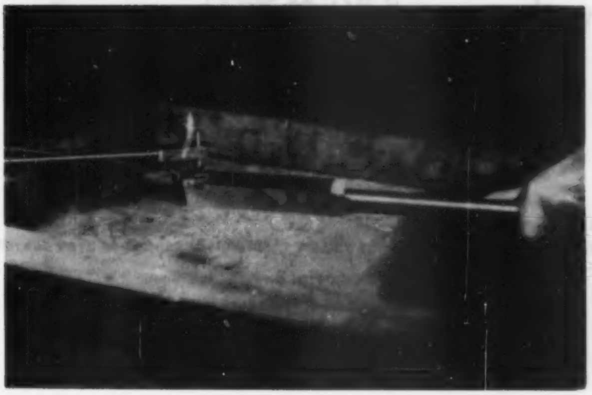

Fig. 6
Photograph of β-chip-samples

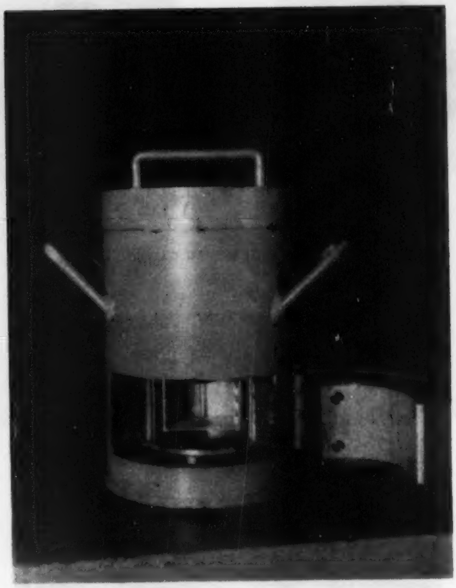

Fig. 7
Measuring set up for β-technique

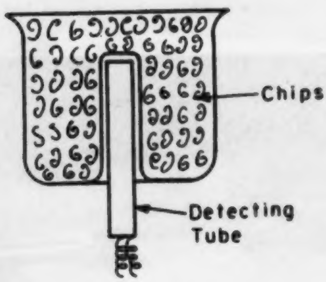

Fig. 8
Principle of γ-measurement

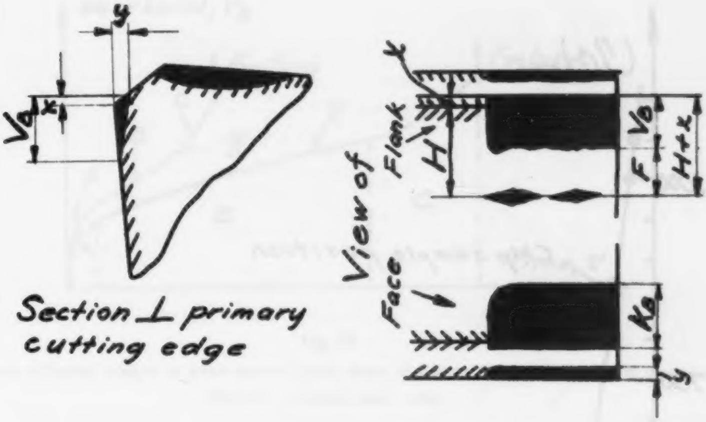

Fig. 9

Important dimensions measured with the microscopic-photographic technique.

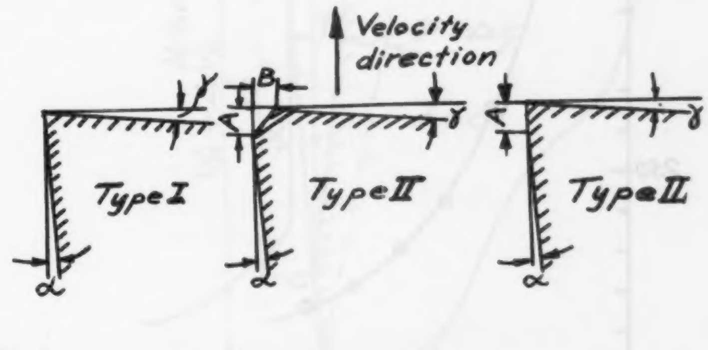

Fig. 11

Three different ways of stoning the primary cutting edge (Sections perpendicular to the edge)

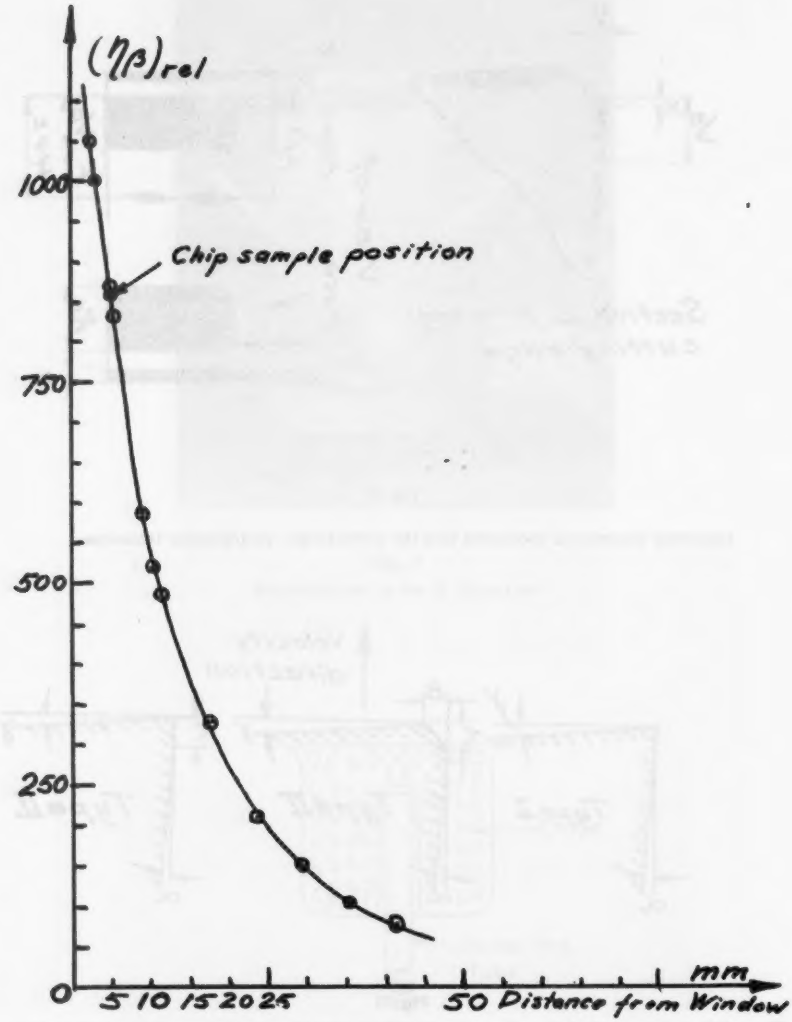

Fig. 10

Variation of geometrical efficiency of GM-tube with distance between sample and end window

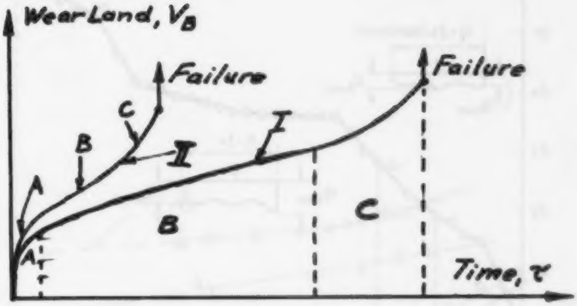

Fig. 12

The three different stages of wear before break down of a tool: A = initial wear; B = normal wear; C = catastrophic wear

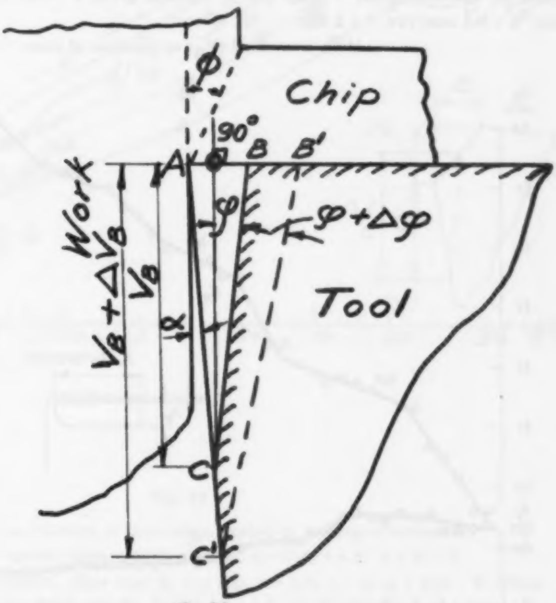

Fig. 16

Section perpendicular to primary cutting edge.

γ = rake-angle set to 0^0; α = clearance angle;

φ = angle of plane of wear; V_B = mean wear land;

ϕ = shear angle.

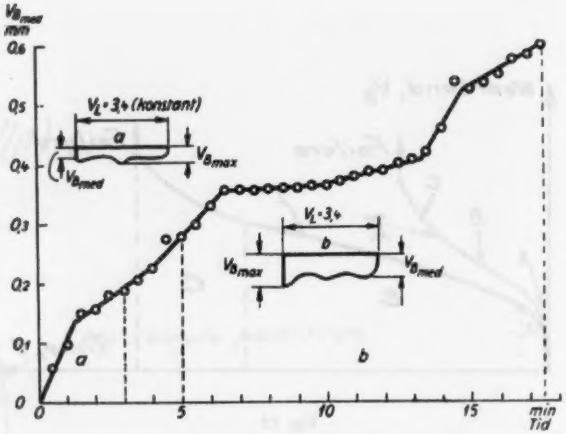

Fig. 13a

Example of "cascading wear". Edge type I. Carbide grade 1 – 0.60 % carbon steel. v = 100 m/min, s = 0.5 mm/rev, t = 2 mm

a) Mean wear land ($\bar{V}_B$) as function of time

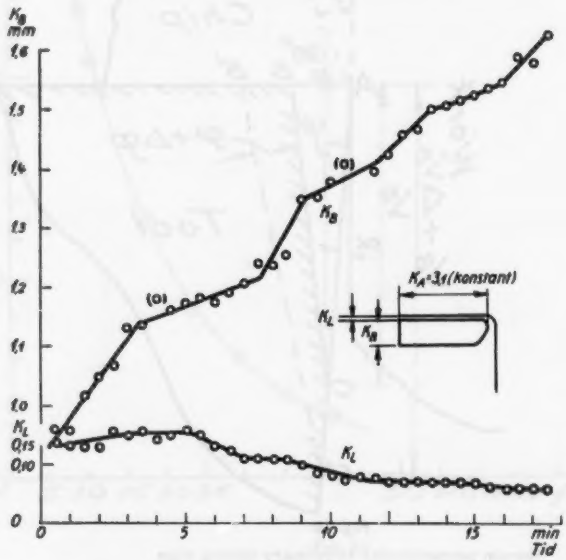

Fig. 13b

b) Crater length (K_B) and distance defined by (K_L) as function of time.

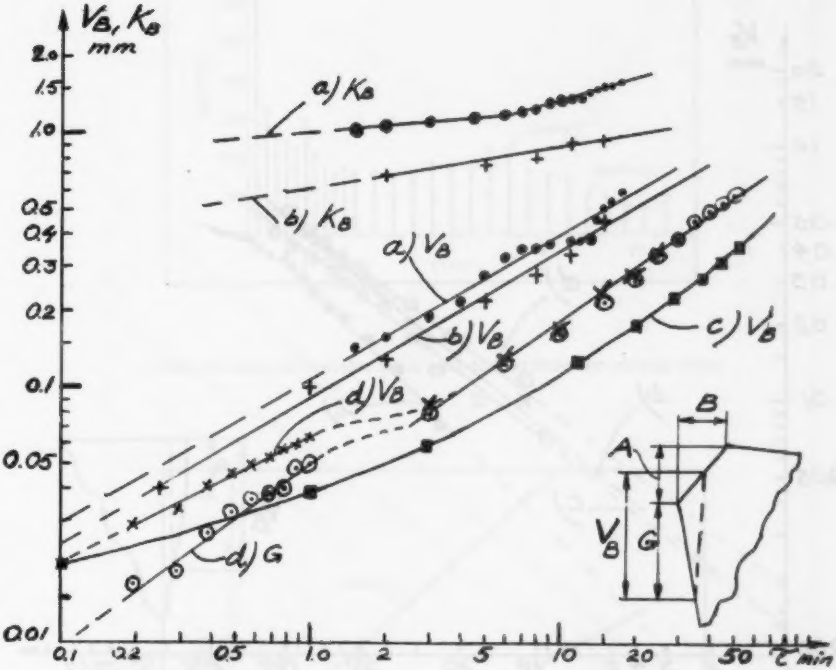

Fig. 14

Flank and Face Wear as function of time when plotted on log-log-coordinates.

a) Grade 1 – 0.60 % C-steel. Edge type I, v = 100, s = 0.5, t = 2, A = B = 0.

b) Grade 2 – 0.60 % C-steel. Edge type II, v = 100, s = 0.5, t = 2, A = 50μ, B = 60μ.

c) Grade 2 – CrNi-steel. Edge type II, v = 60, s = 0.5, t = 2, A = 90μ, B = 110μ.

d) Grade 2 – CrNi-steel. Edge type II, v = 80, s = 0.5, t = 2, A = 100μ, B = 140μ.

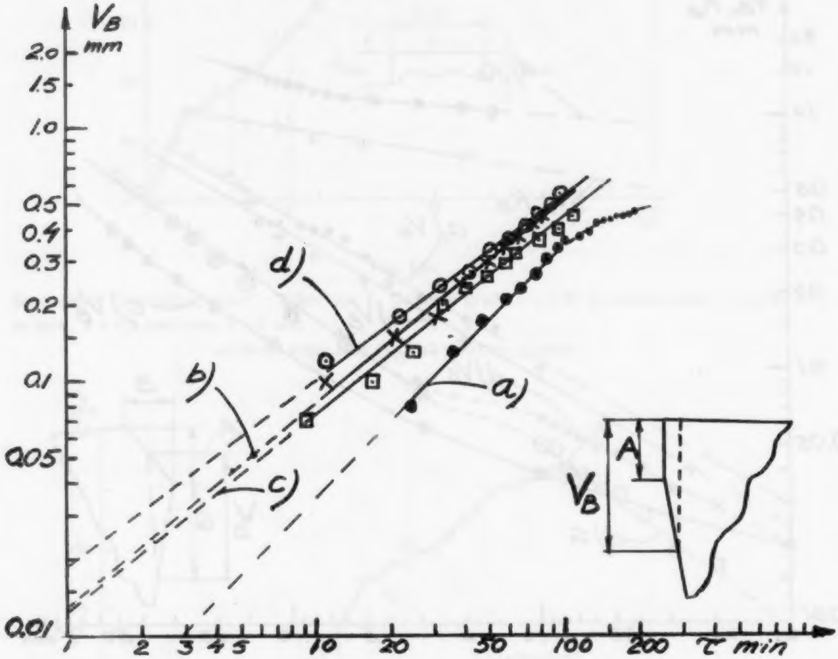

Fig. 15

Grade 1 – CrNi-steel. Edge type III, s = 0.5, t = 2.

a) v = 20; b) v = 30; c) v = 40; d) v = 50

A = 70μ A = 100μ A = 110μ A = 100μ

Fig. 16 see page 49.

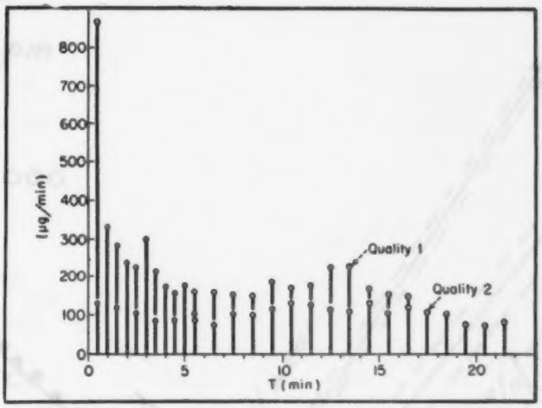

Fig. 17a
a) Rate of material transfer from rake face at different cutting times

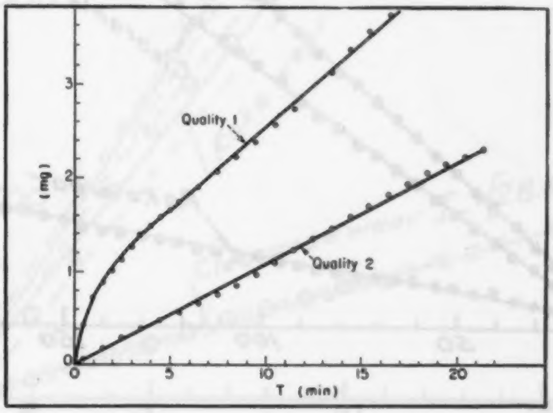

Fig. 17b
b) Integrated wear from rake as function of time. Carbide grades 1 and 2 – 0.60 % Carbon
v = 100, s = 0.5, t = 2

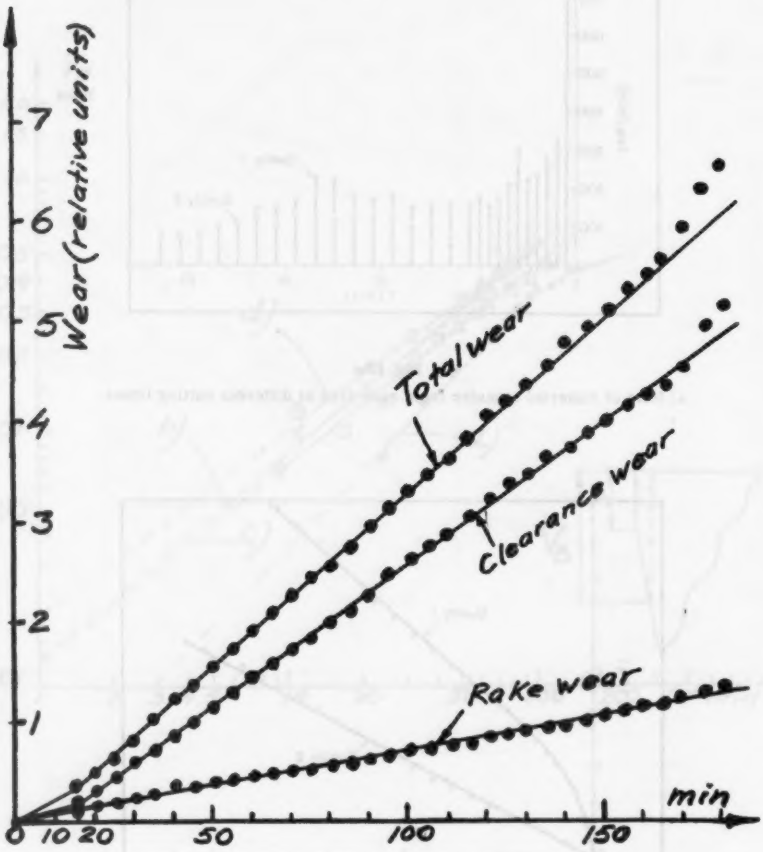

Fig. 18

Rake and clearance wear as function of cutting time. Carbide grade 2 – 0.60 % carbon steel. v = 50, s = 0.5, t = 2. The cutting time of 180 minutes correspond to V_B = 1.5 mm (compare Table V)

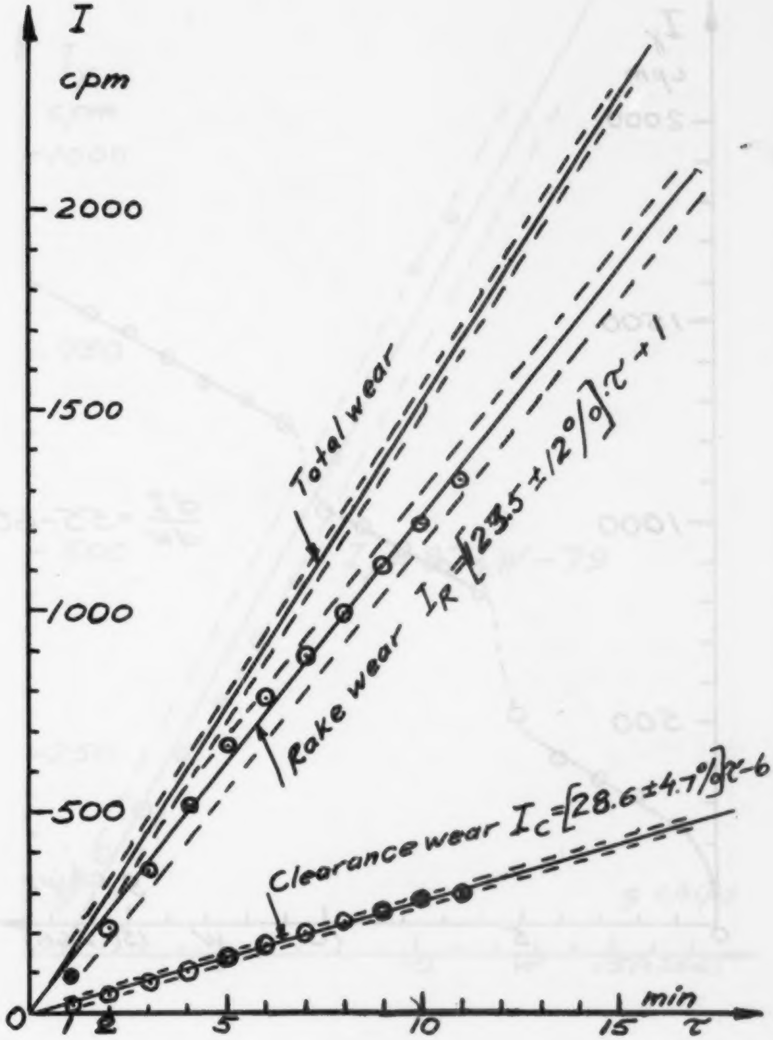

Fig. 19

Rake and Clearance wear as function of cutting time. Carbide grade 1 – 0.60 % carbon steel. v = 100, s = 0.5, t = 2. The cutting time of 11 minutes corresponds to V_B = 0.45 mm.

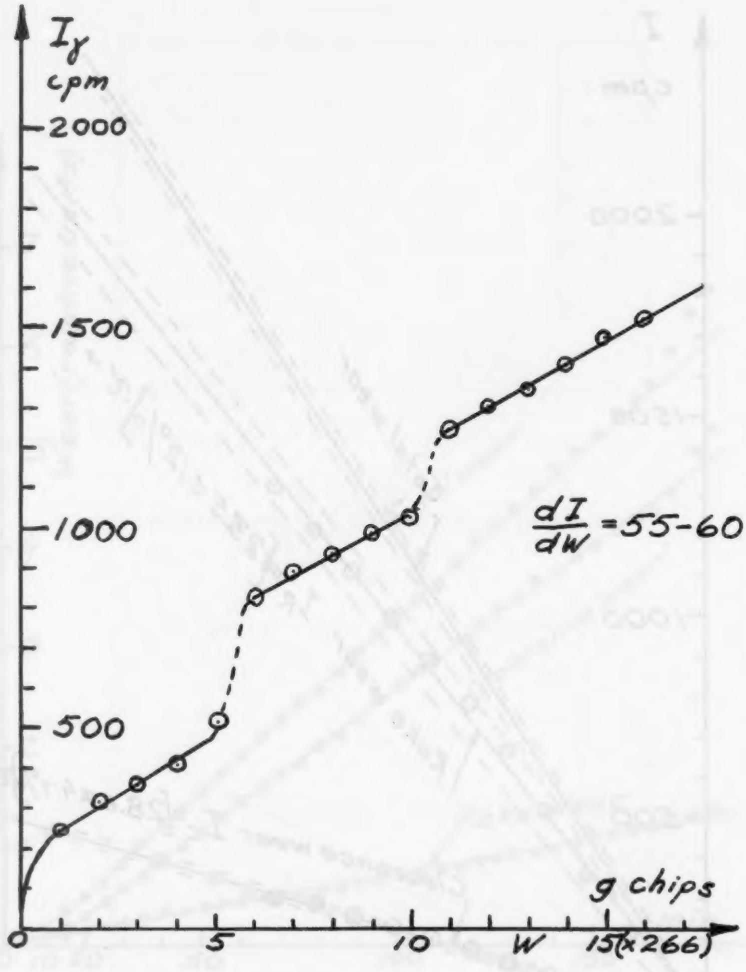

Fig. 20a

**γ-tests using carbide grade 1 – 0.60 % carbon steel. v = 50, s = 0.5, t = 2.
Total wear as function of time up to 9 minutes of cutting. All the chips were collected.**

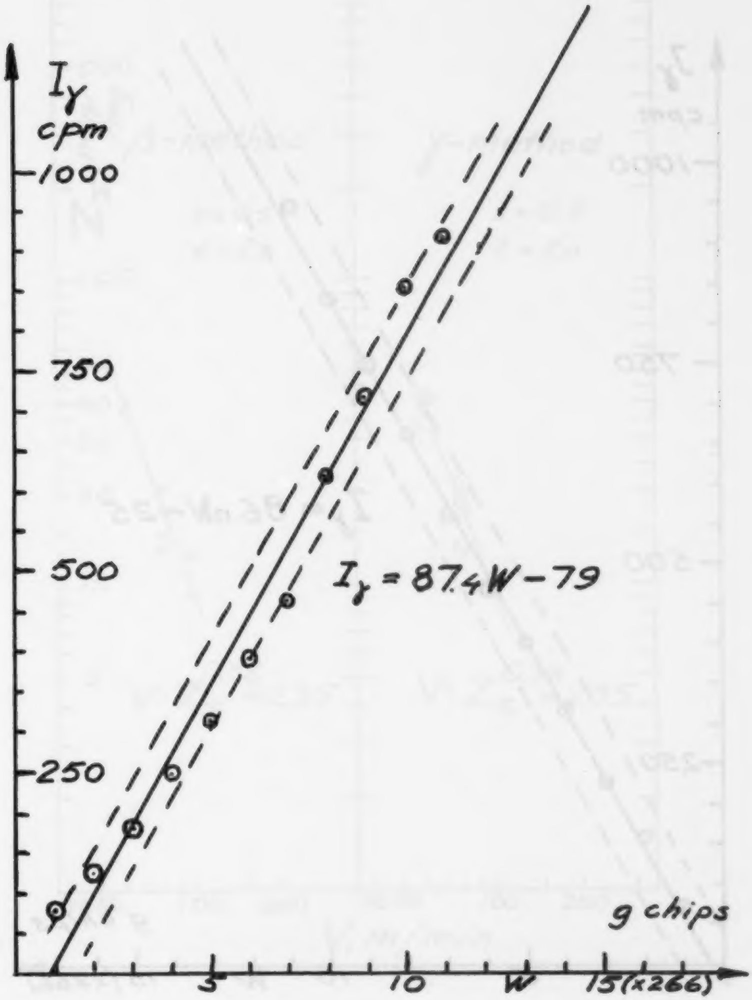

Fig. 20b

γ-tests using carbide grade 1 – 0.60 % carbon steel. v = 50, s = 0.5, t = 2.
Total wear as function of time integrated from cutting times between 20 and 130 minutes.

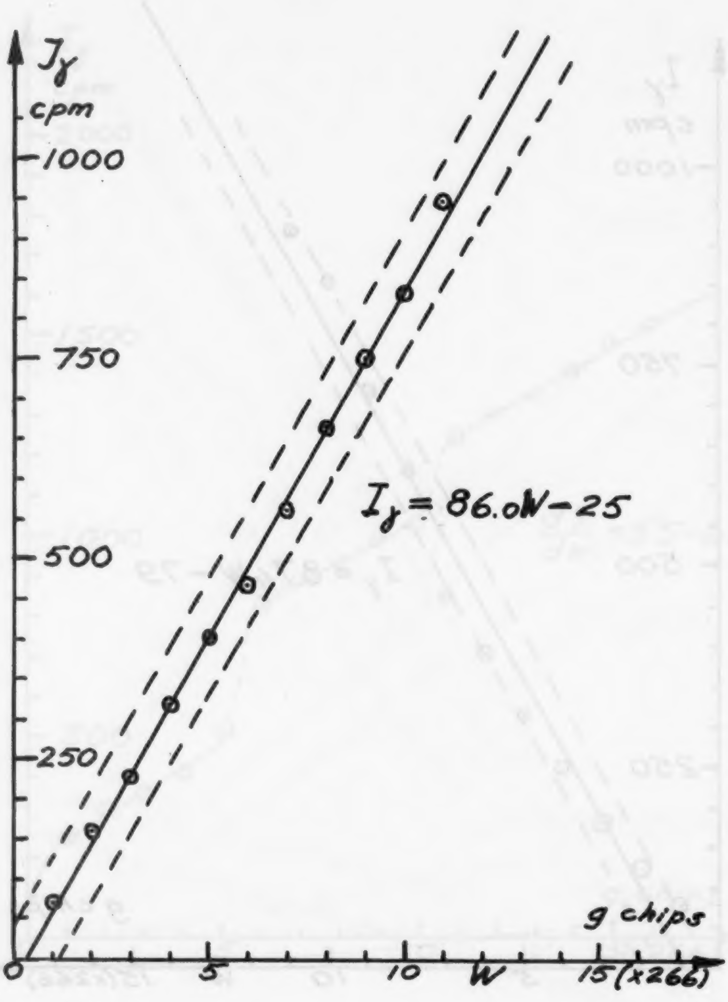

Fig. 20c

γ-tests using carbide grade 1 – 0.60 % carbon steel. v = 50, s = 0.5, t = 2.
Total wear as function of time, integrated from 50.0 to 57.7 minutes of continous cutting.
All chips collected.

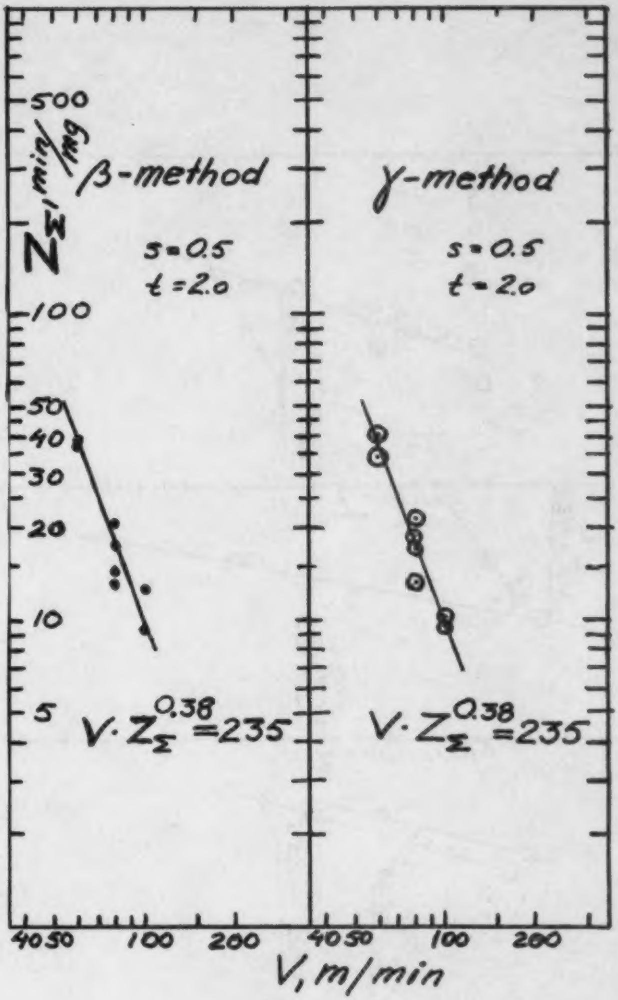

Fig. 21a, b

Total wear rate (Z_Σ) as function of cutting speed. Carbide grade 2 – CrNi-steel. s = 0.5, t = 2.
a) using the β-method, b) using the γ-method.

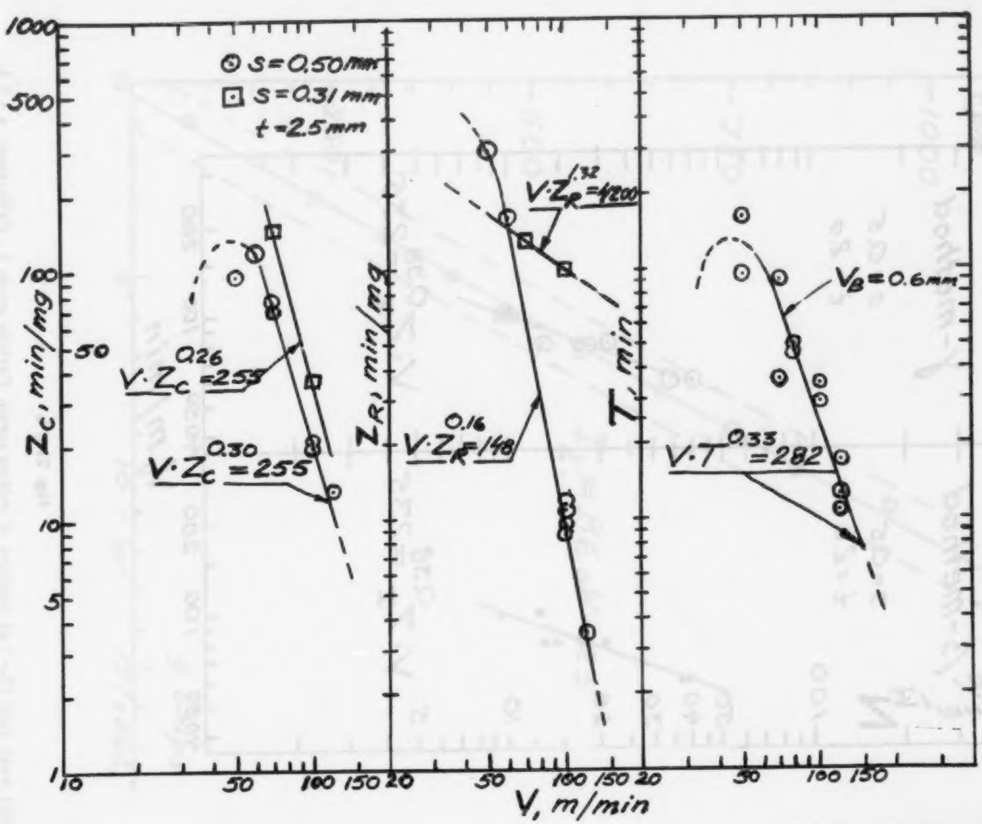

Fig. 22a, b, c

a and b) Z_C and Z_R as functions of cutting speed.

c) Tool-life as function of cutting speed when using the conventional method. The material combinations are -Grade 2 vs. 0.60 % C-steel

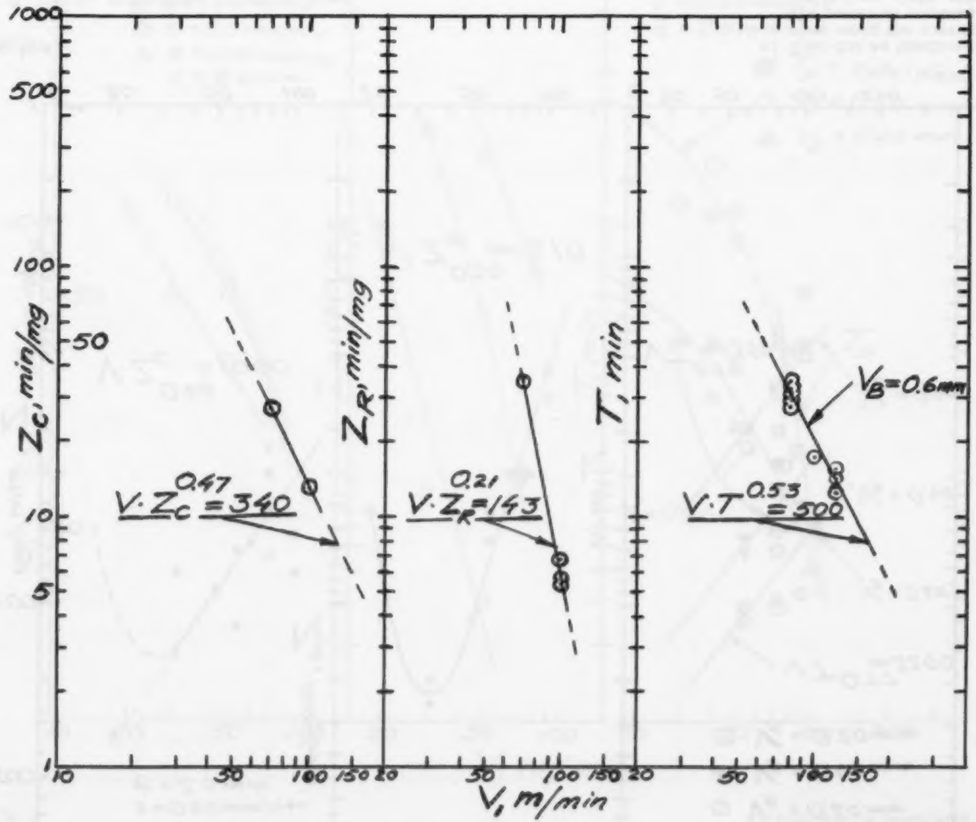

Fig. 23a, b, c

a and b) Z_C and Z_R as functions of cutting speed.

c) Tool-life as function of cutting speed when using the conventional method. The material combinations are Grade 1 vs. 0.60 % C-steel

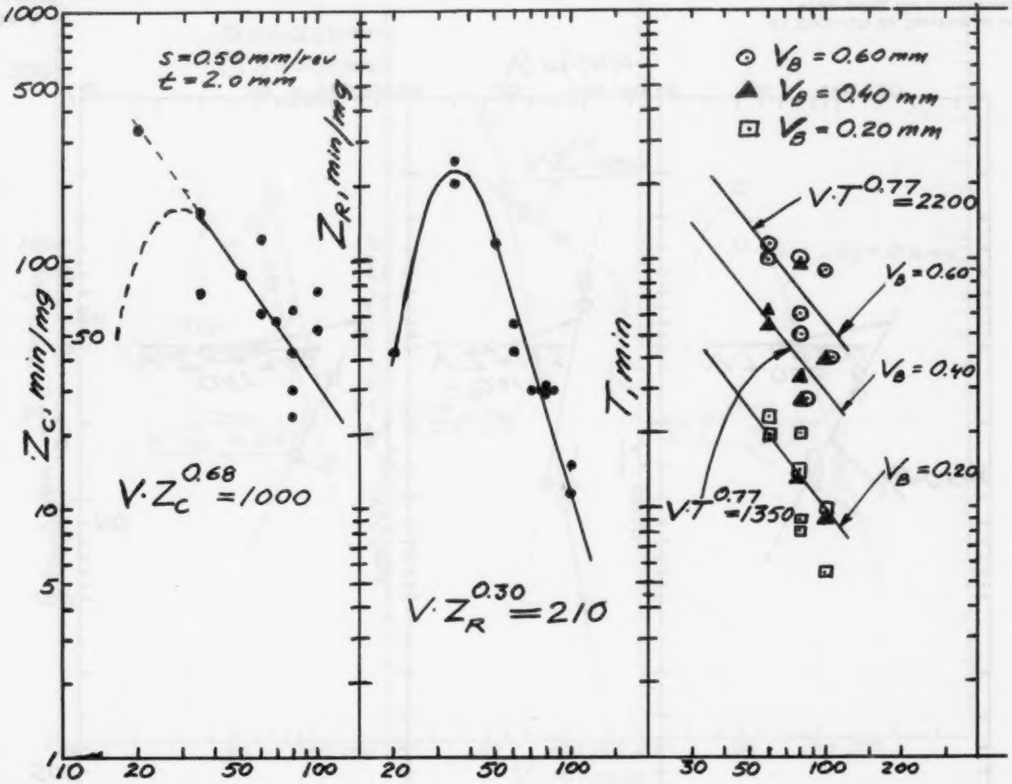

Fig. 24 a, b, c

a and b) Z_C and Z_R as functions of cutting speed.

c) Tool-life as function of cutting speed when using the conventional method. The material combinations are Grade 2 vs. CrNi-steel

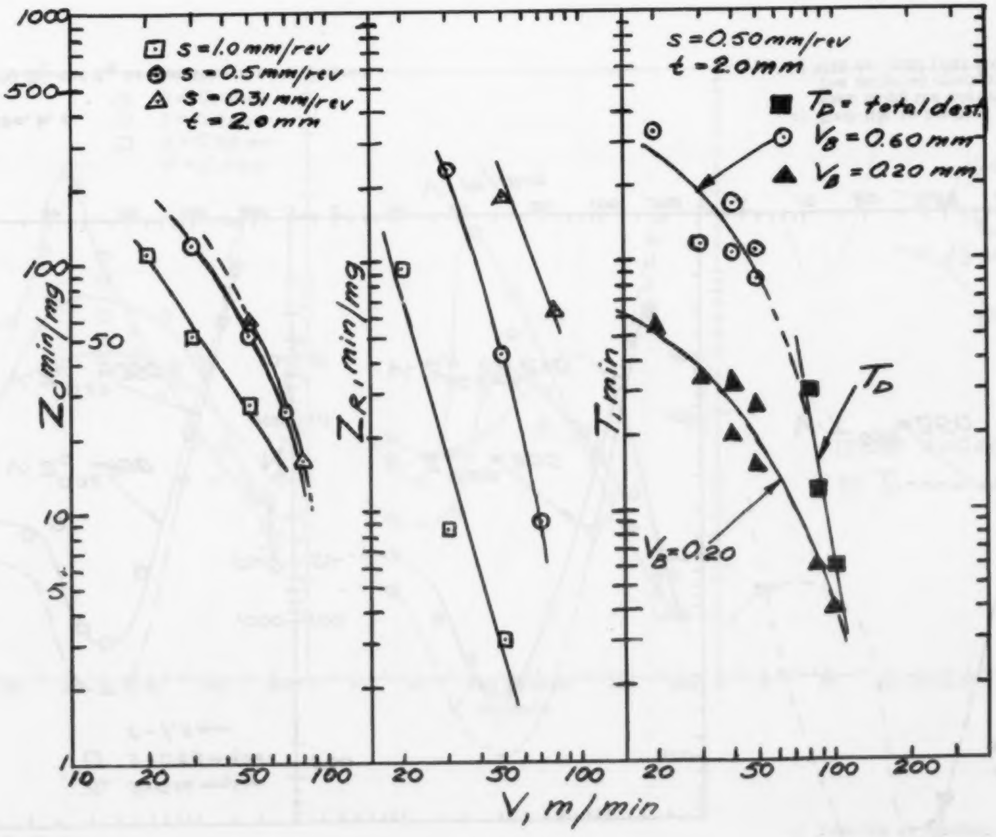

Fig. 25a, b, c

a and b) Z_C and Z_R as functions of cutting speed.

c) Tool-life as function of cutting speed when using the conventional method. The material combinations are Grade 1 vs. CrNi-steel.

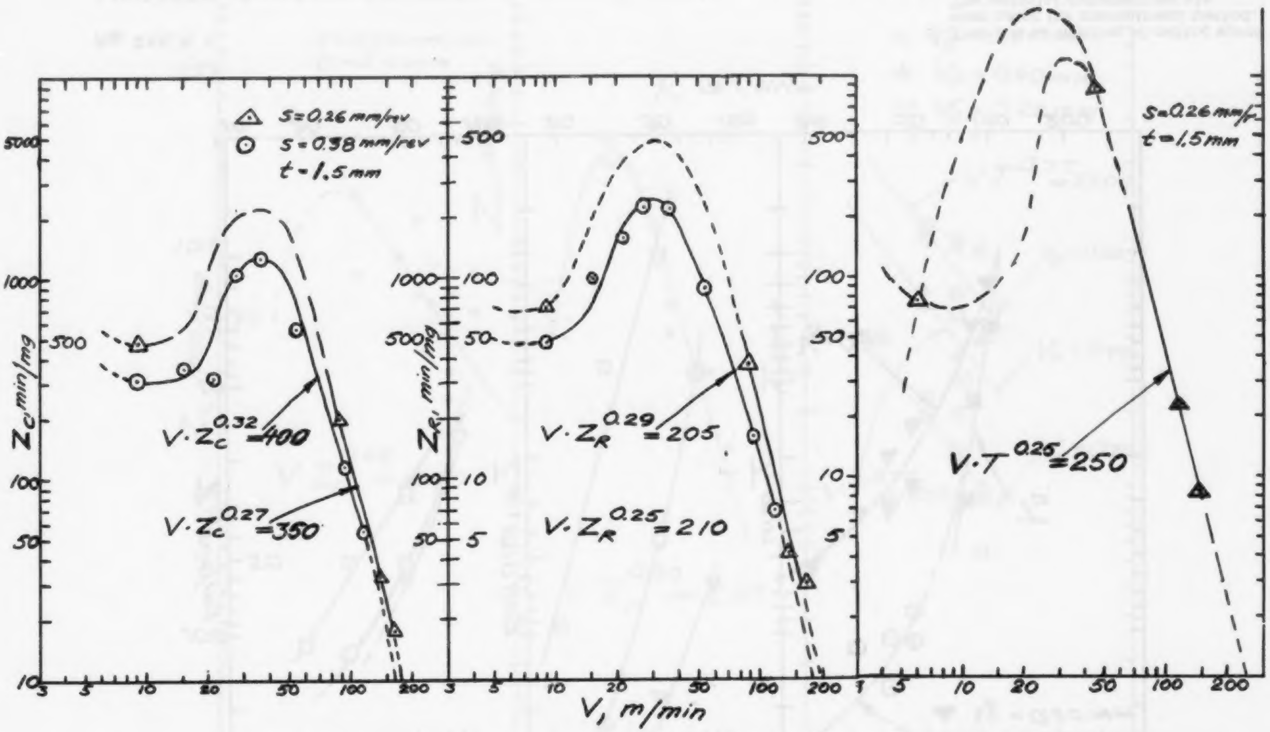

Fig. 26a, b, c

a and b) Z_C and Z_R as functions of cutting speed.

c) Tool-life as function of cutting speed when using the conventional method. The material combinations are K2S vs. AISI 1045 steel

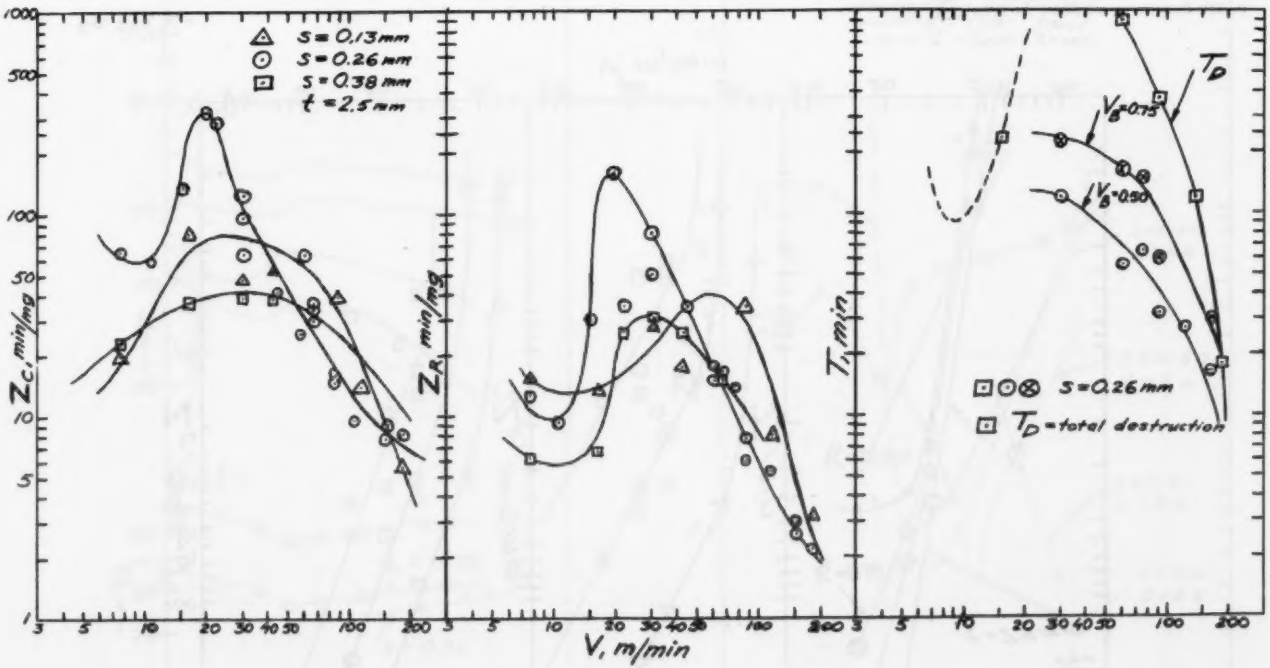

Fig. 27a, b, c

a and b) Z_C and Z_R as functions of cutting speed.

c) Tool-life as function of cutting speed when using the conventional method. The material combinations are K28 vs. AISI 4340

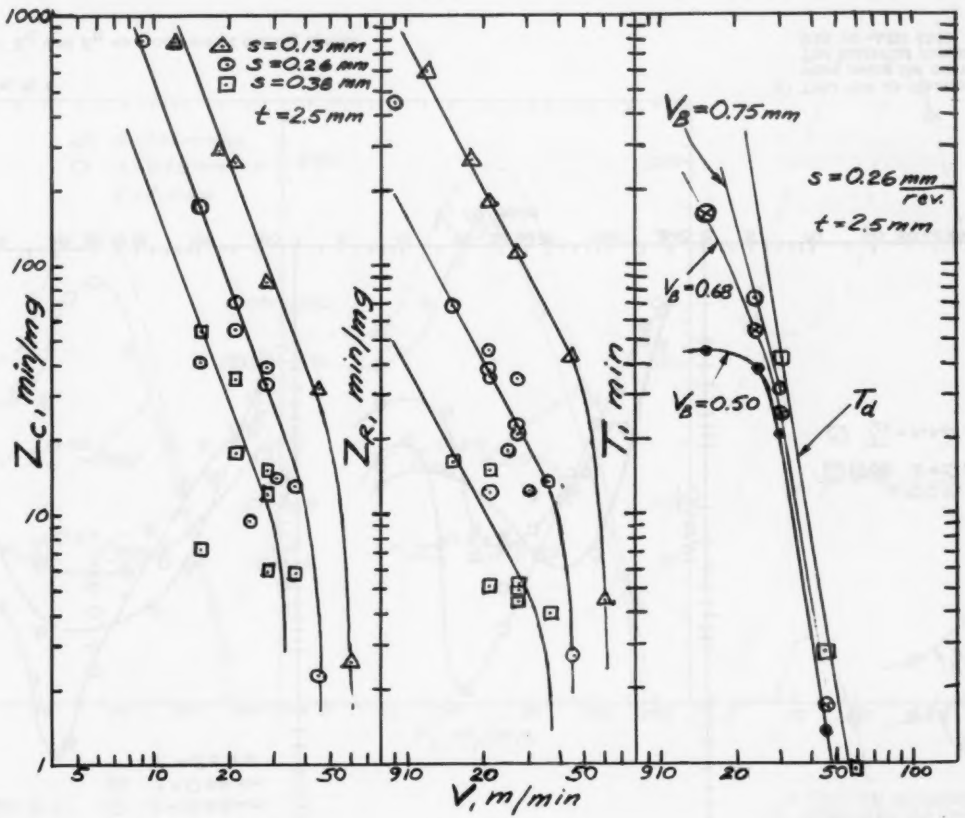

Fig. 28a, b, c

a and b) A_C and Z_R as functions of cutting speed.

c) Tool-life as function of cutting speed when using the conventional method. The material combinations are K2S vs. C130AM titanium.

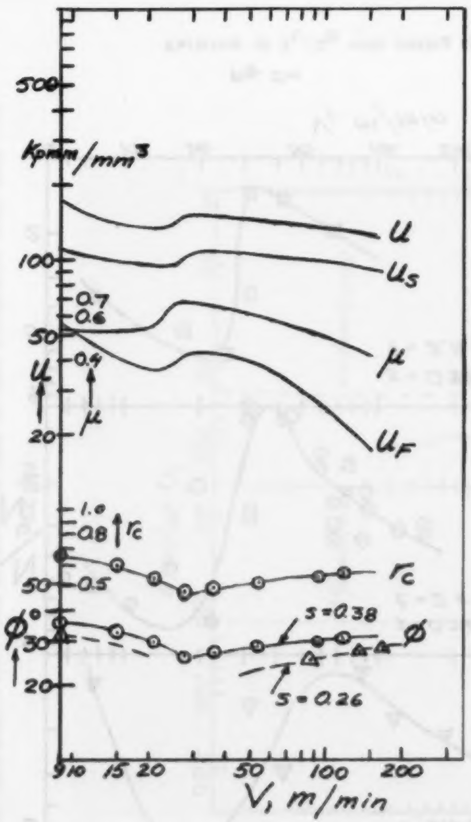

Fig. 29 Cutting energy (u), coefficient of friction (μ), chip thickness ratio (r_c) and shear angle (ϕ), as function of cutting speed. Cutting data the same as in Fig. 26.

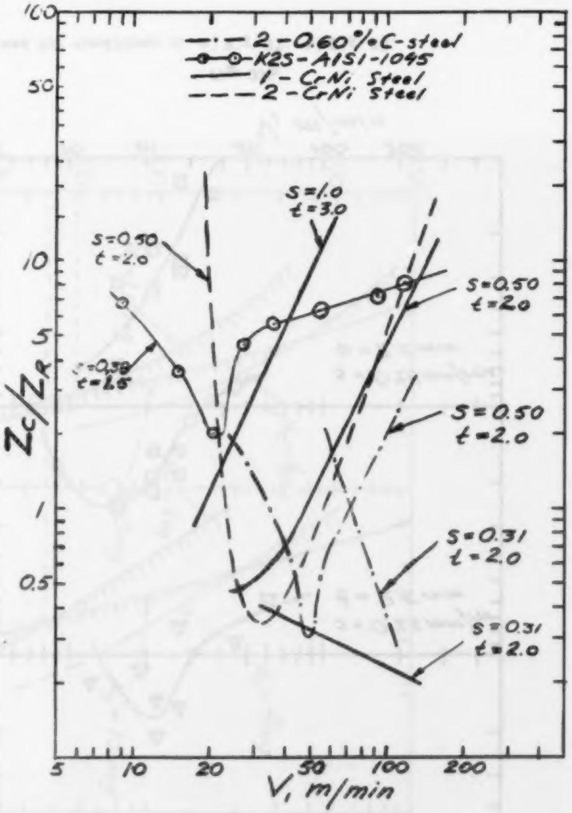

Fig. 30 Variation of Z_C/Z_R with cutting speed and feed for conditions of Fig. 22-26.

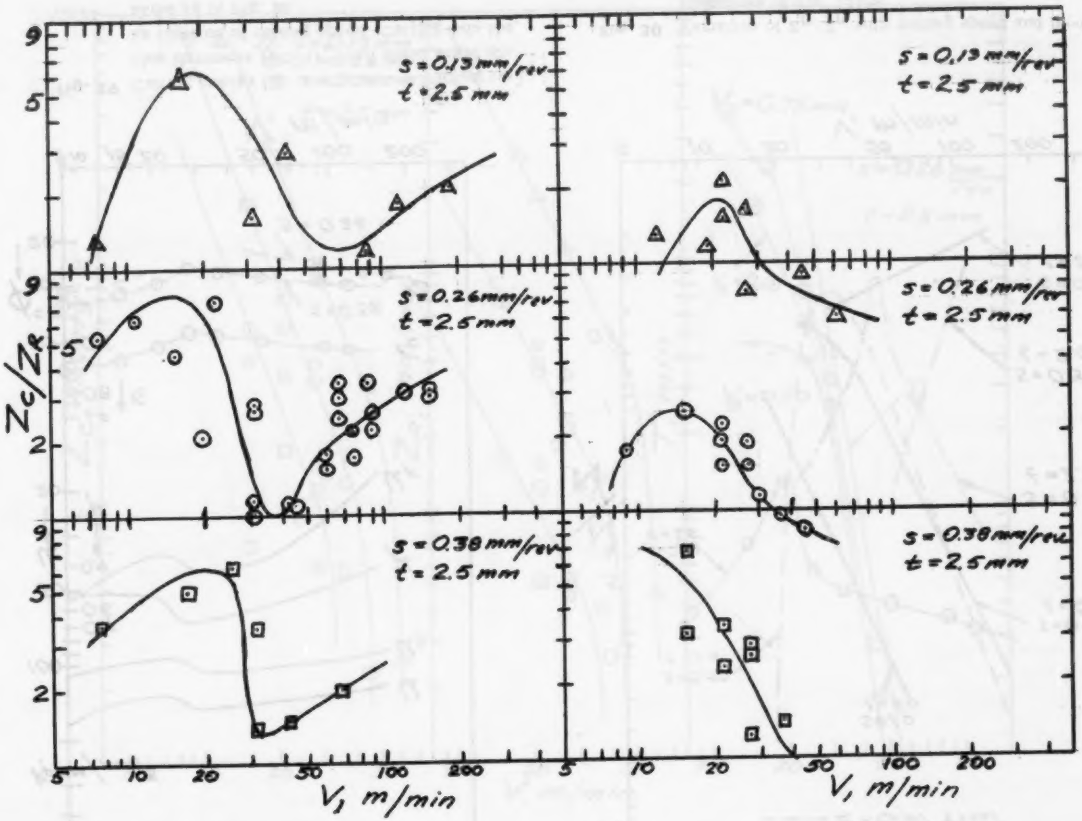

Fig. 31a

Fig. 31b

Variation of Z_C/Z_R with cutting speed and feed for conditions of a) Fig. 27; b) Fig. 28.

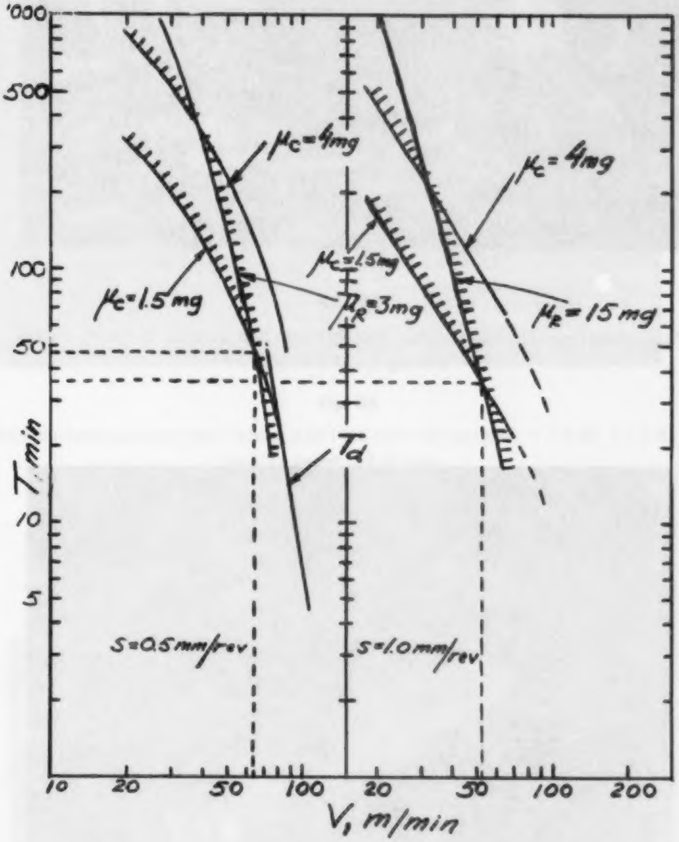

Fig. 32

Tool-lives when considering rake as well as clearance wear when cutting CrNi-steel with carbide grade 1

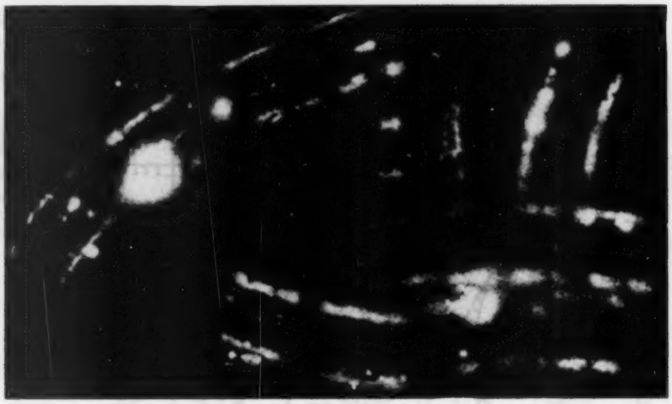

Fig. 33

Chip autoradiographs when cutting AISI 1045 with K2S carbide. s = 0.26, t = 1.5. Cutting speed 9 m/min.

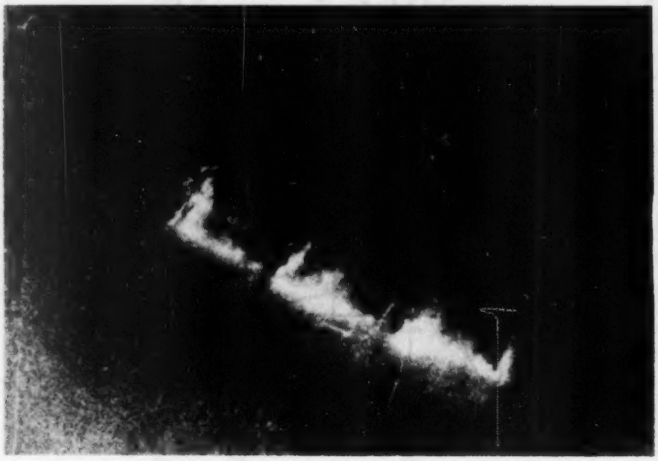

Fig. 34

Chip autoradiographs when cutting AISI 1045 with K2S carbide. s = 0.26, t = 1.5. Cutting speed 87 m/min.

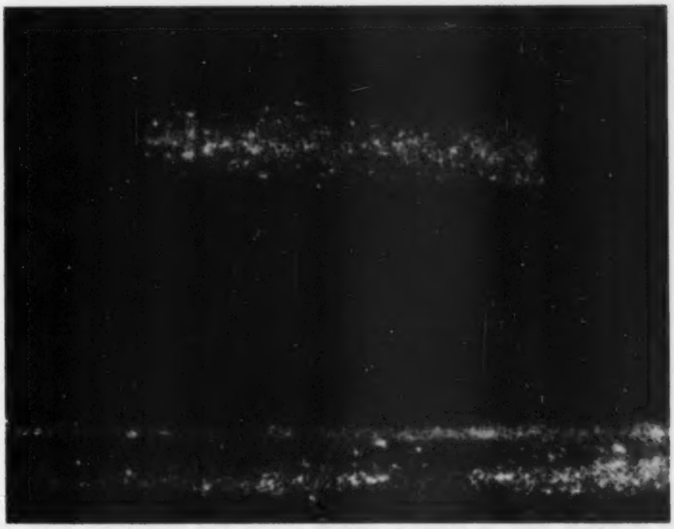

Fig. 35

Chip autoradiographs when cutting AISI 1045 with K2S carbide. s = 0.26, t = 1.5.
Cutting speed 137 m/min.

Fig. 36

Chip autoradiograph. s = 0.38 mm/rev., t = 1.5
Cutting speed 9 m/min.

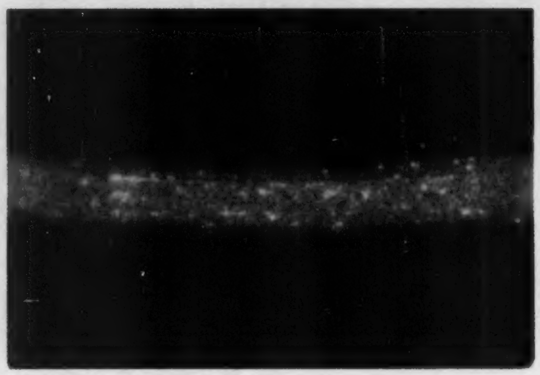

Fig. 37

Chip autoradiograph. Carbide grade 2 vs. 0.60 % C-steel.
v = 100, s = 0.5, t = 2.

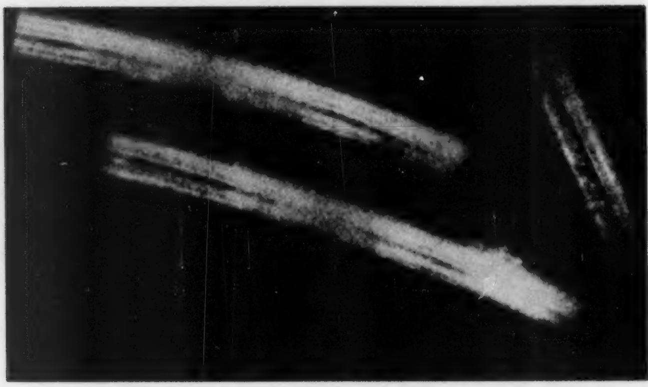

Fig. 38

Picture 5: $S3_2$-1. Chip autoradiograph. Carbide grade 2 vs. CrNi-steel.
T = 0,2 min, I = 1850 ipm/300 mm^2, v = 100 m/min.,
s = 0.5 mm/rev., t = 2.

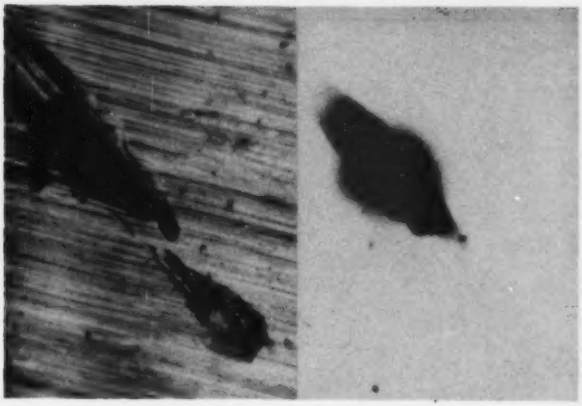

Fig. 39

Chip having abnormally high activity because of broken off piece of carbide tool. (Top) Autoradiograph. (Bottom) Micrograph.

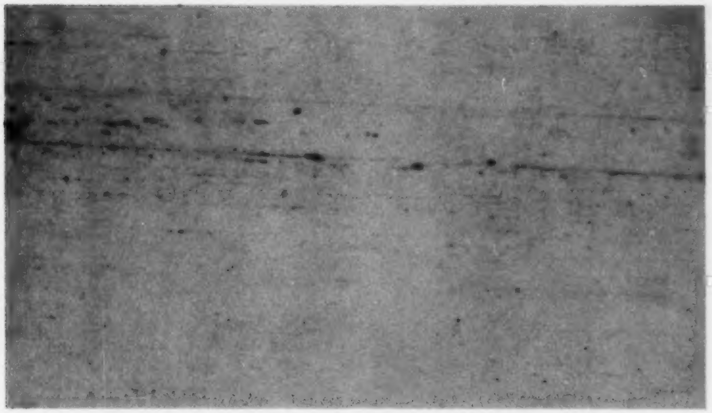

Fig. 40

Autoradiograph of work piece after turning.

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